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**RADC-TR-81-401**  
Final Technical Report  
February 1982



## **M-QAM MODEM VERIFICATION**

**Harris Government Communications Division**

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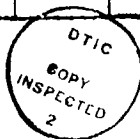
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64. The breadboard was to operate within the constraints of FCC Docket 19311 and achieve spectral efficiencies of 1.5, 3.0, and 4.5 bits/sec/Hz for  $M = 4, 16,$  and 64.

The breadboard was constructed and tested and the adaptive predistortion and baseband equalizer techniques proven feasible. Performance curves are presented for the various modes ( $M = 4, 16,$  and 64) for back-to-back operation as well as through a simulated microwave link. Performance for various levels of TWT power backoff when predistortion is enabled or disabled and when the baseband equalizer is enabled or disabled are presented.

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## 1.0 INTRODUCTION

### 1.1 Objective

The objective of this program was to verify the technical feasibility of the variable mode M-ary Quadrature Amplitude Modulation (M-QAM) concepts discovered under Contract F30602-77-C-0039 ("Linear Modulation Techniques for Digital Microwave")<sup>1</sup> and Contract F30602-79-C-0072 ("ECCM for DCS III").<sup>2</sup> Specifically, the adaptive predistortion and baseband equalizer techniques were to be breadboarded and evaluated for M-QAM modes for M=64, 16, and 4, where M is equal to the number of signal points in the signal constellation. The breadboard was to operate within the spectral constraints of FCC Docket 19311 and achieve spectral efficiencies of 1.5, 3, and 4.5 b/s/Hz when operating in the 4, 16, and 64-QAM modes, respectively. The bit error rate (BER) performance design objective was a BER of  $1 \times 10^{-9}$  at a measured  $E_b/N_0$  of 13.5, 19.5, and 22.5 dB when operating at 1.5, 3, and 4.5 b/s/Hz, respectively.

### 1.2 Approach

The program consisted of two phases. During the first phase, the design plan developed on Contract F30602-77-C-0039 was reviewed and modified as required by the results of Contract F30602-79-C-0072. A design plan based upon the review was generated and submitted. In the second phase, the breadboard was fabricated and evaluated over a simulated microwave link and in back-to-back modes.

Since receiver symbol tracking and carrier tracking loops were not considered a factor in proving the adaptive predistortion and baseband equalizer techniques, they were not included in the design. Instead, symbol timing and carrier timing were hardwired over from the transmitter.

### 1.3 Results

An authorized bandwidth of 3.5 MHz was selected in order to keep the operating logic speed within the realm of straightforward implementation. Higher speeds could have been achieved had Emitter Coupled Logic (ECL) been available with reasonable delivery dates. Use of ECL would have allowed operation at authorized bandwidths of 7 or 10.5 MHz.

The adaptive predistortion and baseband equalizer essentially worked as predicted on Contracts F-30602-77-C-0039 and F30602-79-C-0072. Performance was affected by in-phase (I) channel and quadriphase (Q) channel crosstalk caused by filter imperfections. Modification of the baseband equalizer included some crosstalk compensation and improved the performance by 0.5 dB.

Performance goals were not met on this program due to filter imperfections. However, the results clearly indicate that adaptive predistortion and baseband equalization are necessary when operating with bandwidth efficiencies in excess of 3 bits/sec/Hz.

### 1.4 Report Organization

The comparison of results from Contract F30602-77-C-0039 and the hardware built are discussed in Section 2.0. The implementation of the breadboard is discussed in Section 3.0. In Section 4.0, the test program and results are presented. Section 5.0 contains the conclusions and recommendations.

## 2.0 THEORETICAL DISCUSSIONS

It is the purpose of this section to analyze the results of the previous contracts and discuss the affects upon performance introduced by self-synchronizing randomizers and differential encoding.

### 2.1 Summary of Results from Previous Contract

On Contracts F30602-77-C-0039 and F30602-79-C-0072, considerable effort was expended in analyzing and simulating ideal and practical M-QAM schemes. As a point of reference, we will include those results in this section. Figure 2.1-1 shows the ideal performance of M-QAM systems for various values of M. For this effort, we are only interested in the M-QAM curves for M=4, 16, and 64. Figure 2.1-2 presents the predicted performance of M-QAM for M=4, 16, and 64. These curves are derived from simulations based upon using a 5-pole Butterworth transmit filter with 3 dB bandwidth equal to the symbol rate, and a receive filter whose bandwidth is approximately 30 percent wider than symbol rates at the 3 dB points. The simulation also includes second order phase compensation for the transmit filter.

It should be noted at this time that these curves are for symbol error rate, not bit error rate. To obtain bit error rate, subtract 0.2 dB from the M=4 curve, 0.4 dB from the M=16 curve, and 0.5 dB from the M=64 curve.

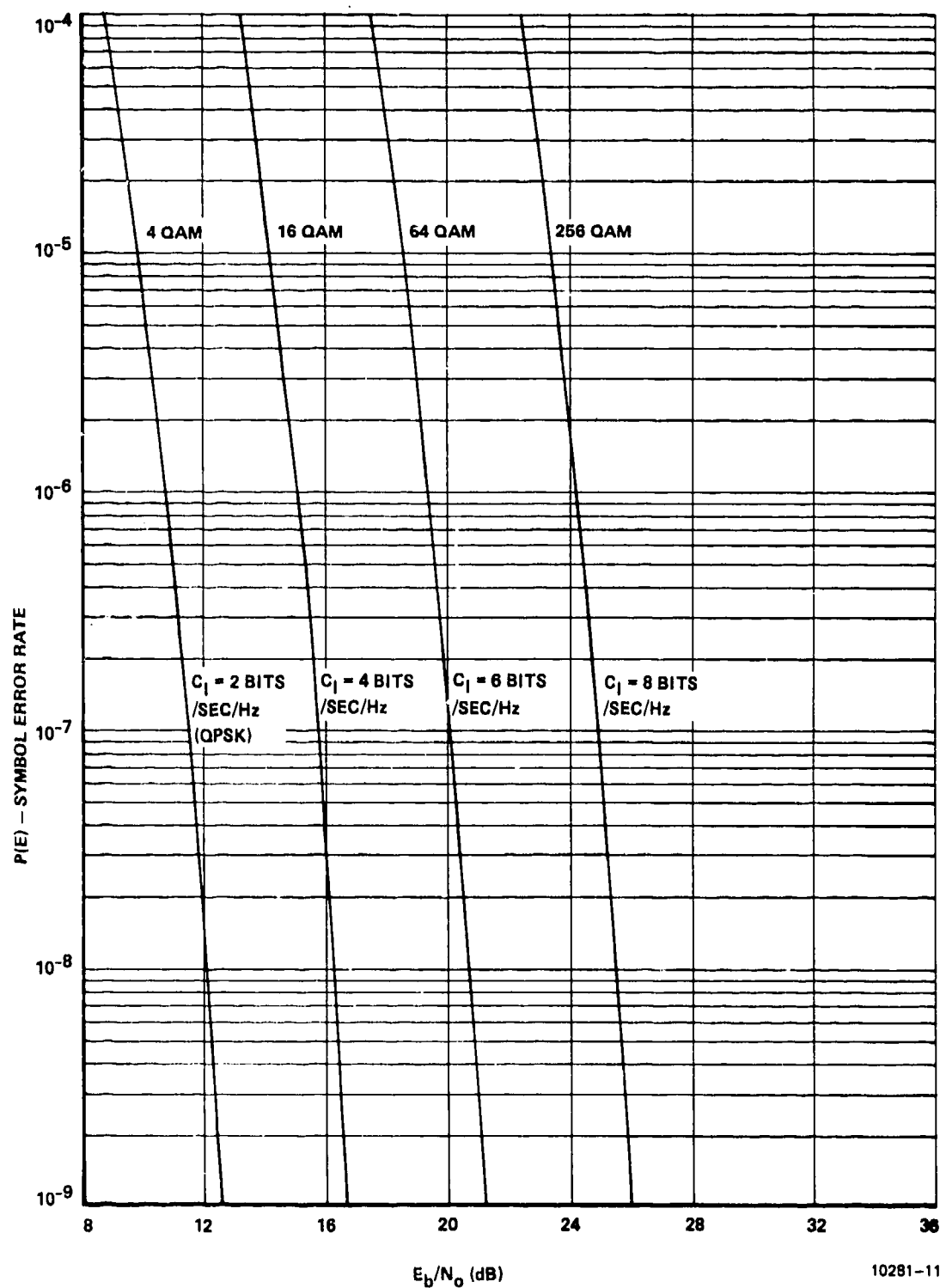


Figure 2.1-1. Ideal M-QAM Performance

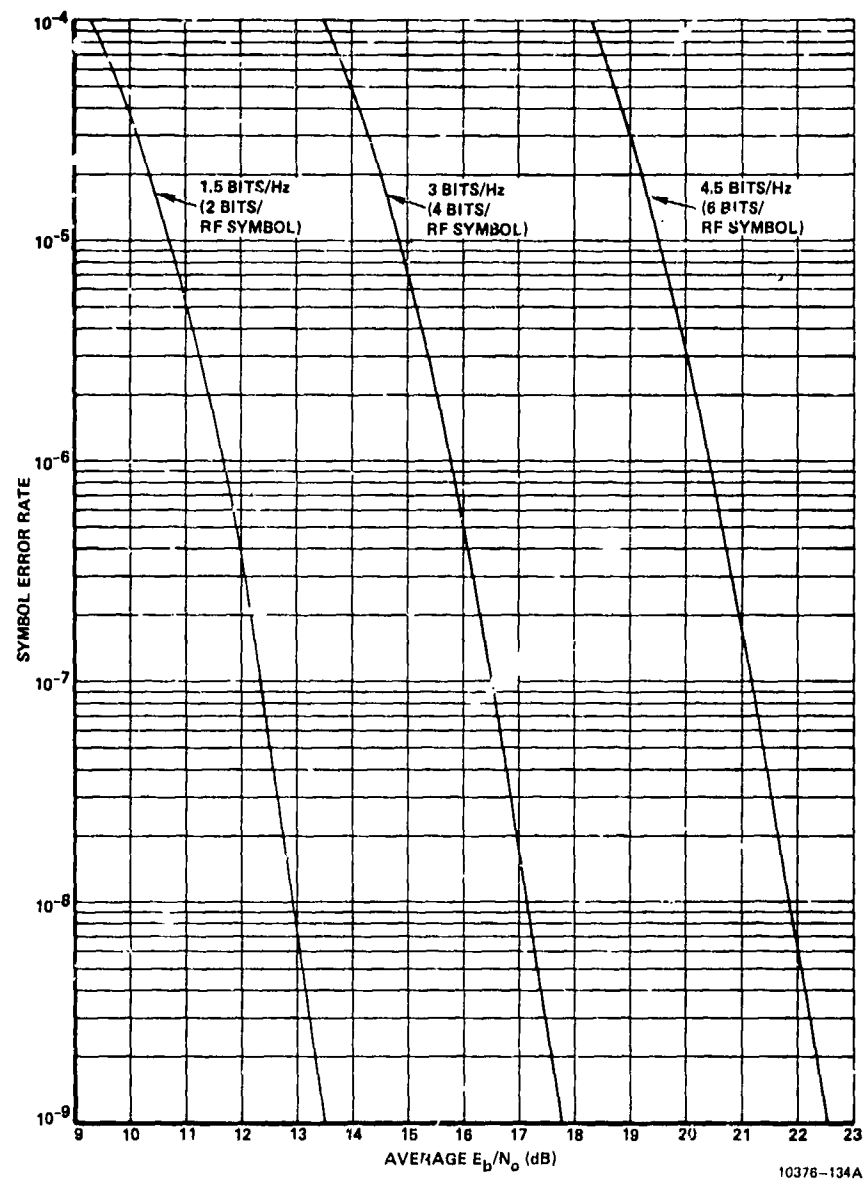


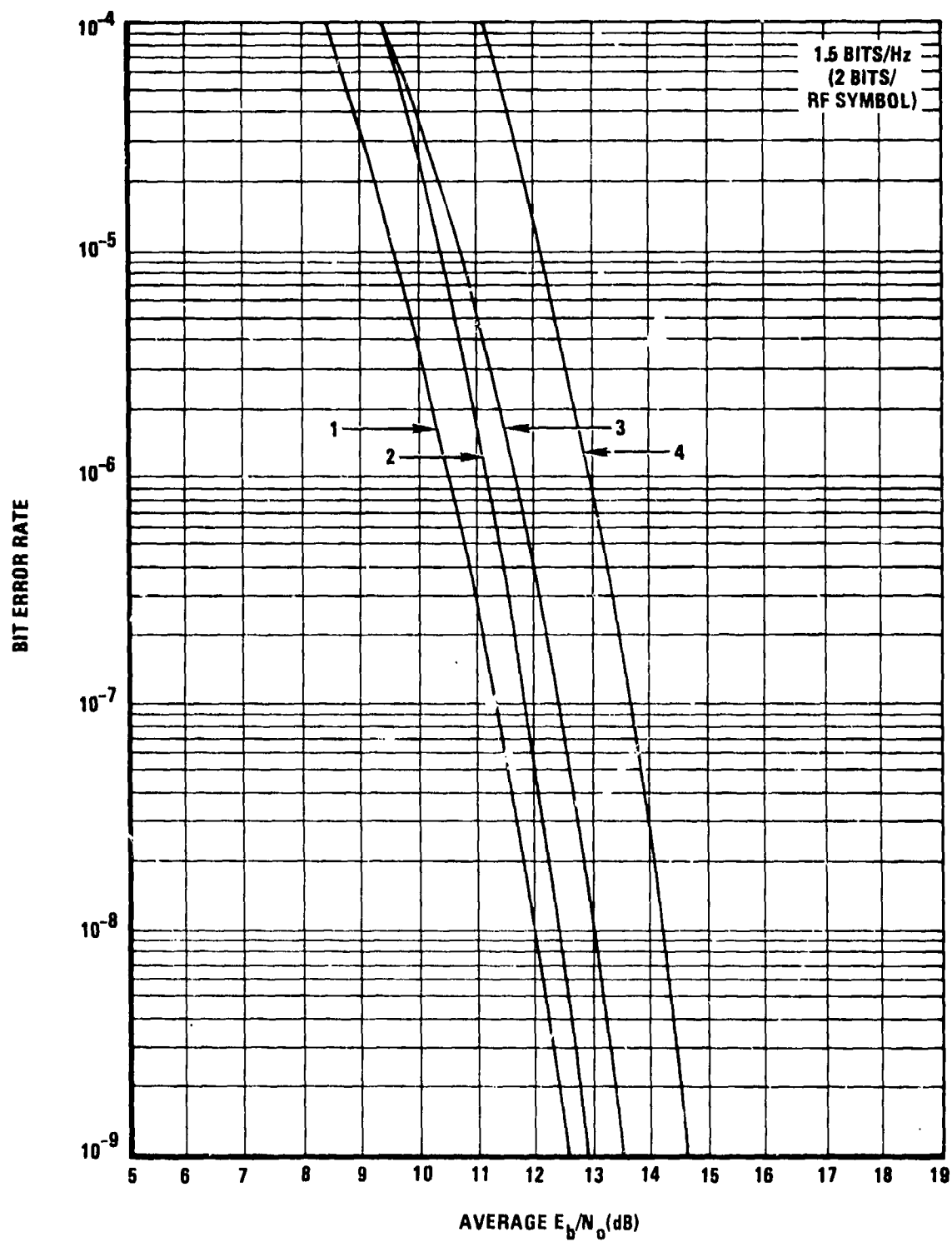
Figure 2.1-2. LMT Practical Hardware Modem Performance

## 2.2 Further Performance Degradation Introduced by Hardware Implementation

The practical M-QAM performance curves presented previously do not take into account the effects caused by differential encoding/decoding and the self-synchronizing randomizer used to randomize incoming data. The differential encoding process introduces single bit errors within a quadrant. However, when passing quadrant boundaries, as many as five bit errors may be introduced for a single symbol error. The self-synchronizing randomizer introduces three bit errors for every bit error made.

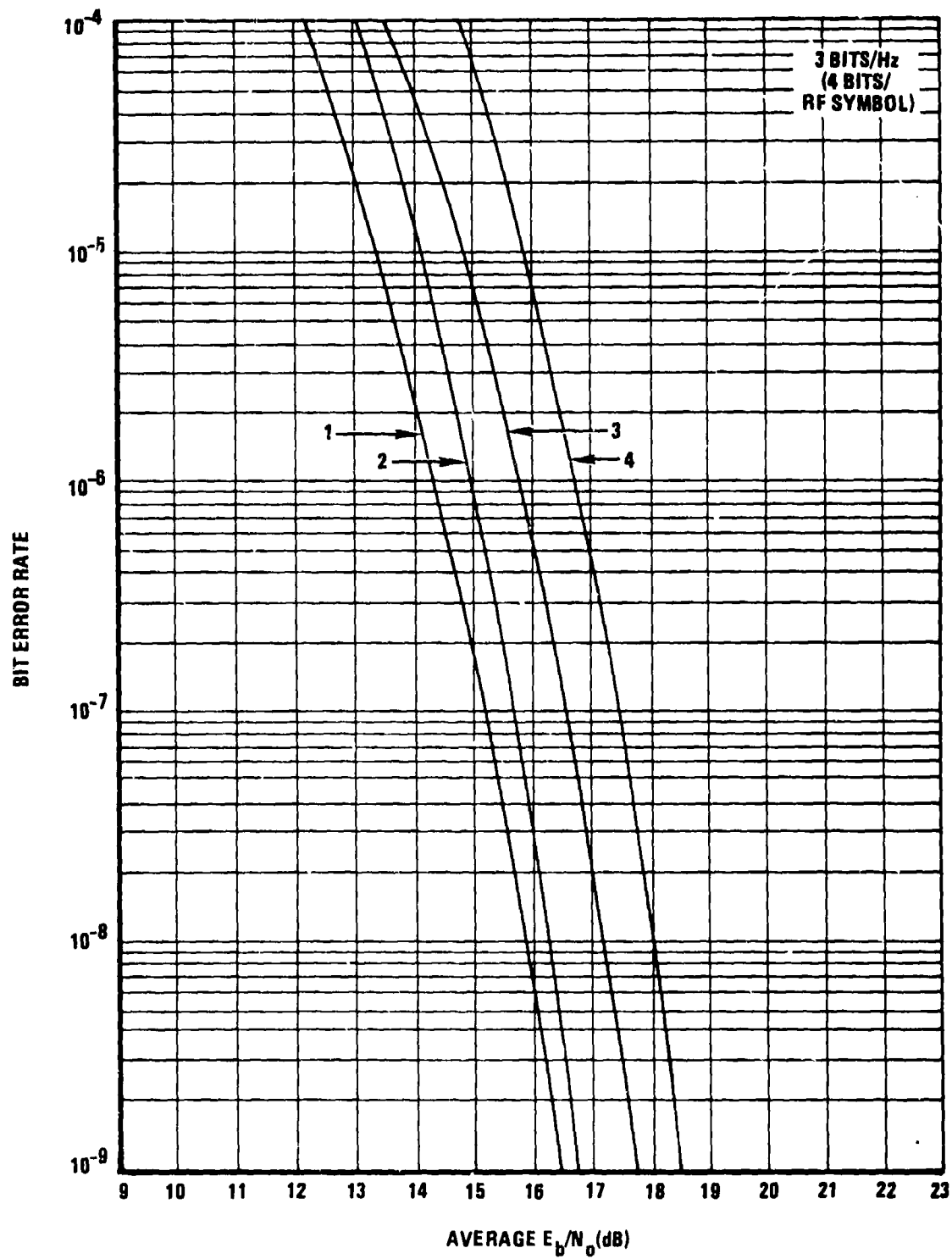
The effects of these two processes are taken into account as shown in Figures 2.2-1 through 2.2-3 ( $M=4, 16$ , and  $64$ , respectively). Curve number 1 in each figure is ideal M-QAM performance, while curve number 2 is ideal M-QAM with the effects of differential encoding and the self-synchronizing randomizer taken into account. Curve number 3 in each figure is practical M-QAM from Contract F30602-77-C-0039, while curve number 4 is practical M-QAM after the inclusion of differential encoding and self-synchronizing randomizer effects.

The difference between ideal and practical performance is  $1.8$  dB, where  $1.5$  dB is due to the difference between the noise bandwidth of an ideal matched filter (integrate and dump) and the noise bandwidth of a 5-pole Butterworth<sup>3</sup> filter with  $3$  dB bandwidth  $40$  percent wider than symbol rate. The additional  $0.3$  dB difference is to account for hardware implementation imperfections.



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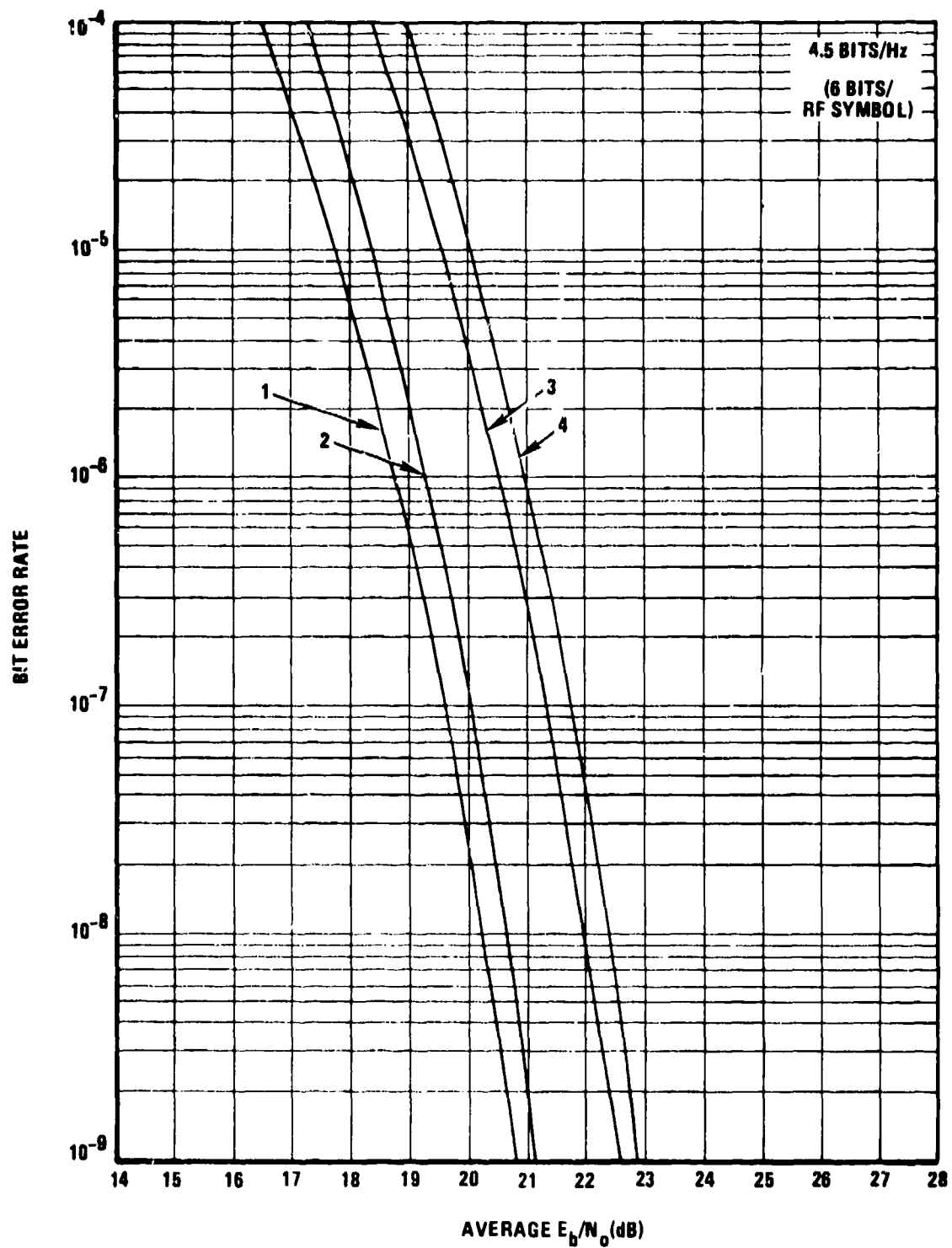
Figure 2.2-1. 4-QAM Practical and Ideal Performance



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Figure 2.2-2. 16-QAM Practical and Ideal Performance





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Figure 2.2-3. 64-QAM Practical and Ideal Performance

### 3.0 HARDWARE IMPLEMENTATION

A breadboard M-ary-QAM Modem based upon the concepts developed on Contracts F30602-77-C-0039 and F30602-79-C-0072 was designed and constructed according to the design plans.<sup>4,5</sup>

#### 3.1 M-QAM Modem

The M-QAM Modem operating bandwidth was selected from the following DCS authorized bandwidths: 3.5, 7, 10.5, 14, 20, and 40 MHz. During the design phase, it was determined that the ECL memories required for straightforward implementation of bandwidths of 7 or 10.5 MHz were not available in less than a year. Based upon parts availability, the authorized bandwidth was chosen to be 3.5 MHz. Bandwidths above 10.5 MHz had been previously dismissed due to the complexity of logic implementation.<sup>4</sup> Demodulator timing and carrier recovery circuits, as well as the input AGC circuitry, were not implemented for this breadboard. Timing and carrier signals were derived from the modulator. Symbol timing was chosen to be 2.625 MHz ( $0.75 \times 3.5$  MHz) which yields bit rates of 5.25, 10.5, and 15.75 Mb/s for  $M=4$ , 16, and 64. These bit rates equate to bandwidth efficiencies of 1.5, 3, and 4.5 b/s/Hz for  $M=4$ , 16, and 64.

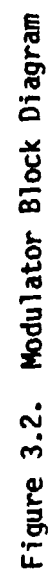
#### 3.2 M-QAM Modulator

The M-QAM modulator, shown in Figure 3.2, consists of three circuit boards: 1) Bit Rate Generation and Distribution, 2) Transmit Logic Board, and 3) Transmit Analog Card. Two crystal oscillators are used to supply timing and carrier; 126 MHz for timing and 70 MHz for carrier. Power is supplied by laboratory power supplies. Power requirements are +5 V (logic), -5.2 V (ECL), and  $\pm 15$  V (analog).

Interface between the transmitter and external sources or sinks are TTL levels into 50 ohms for data and clock, 0 dBm into 50 ohms for the 70 MHz IF output and +15 dBm into 50 ohms for the sampled TWT output. Interfaces between the transmitter and receiver are 0 dBm into 50 ohms for carrier, and TTL levels for clock and control. Internal transmitter interfaces are TTL for clock and data, and 0 dBm into 50 ohms from the oscillators. High rate clocks and data are carried on twisted pair.

The serial data is sampled by the symbol clock and converted from serial-to-parallel format. The number of bits/symbol are 6, 4, and 2 for the three operating modes. The parallel data is then differentially encoded before being used to address the predistortion RAM. The delay unit is used to align read and write addresses to account for cable and filter delays through the modulator. The number of symbols of delay to be provided depends upon the delay through the up and downconversion processor. The output of the delay unit is controlled by the READ/WRITE signal. The predistortion RAM contains the values of the 64 (or 16 or 4) signal points in 12-bit I and Q formats. The RAM output is split into 10 and 12-bit I and Q paths. The 10-bit paths are converted to analog levels for modulation on the 70 MHz I and Q carriers while the 12-bit paths are delayed before being modified by adding or subtracting 1. The updated words are written back into RAM memory.

The 70 MHz oscillator is buffered on the Transmit Analog Card where the signal is split into in-phase and quadrature components and distributed to the transmit modulator and demodulator. A phase-shifted 70 MHz carrier is sent to the receiver for demodulation. The 10-bit in-phase word and 10-bit quadrature word are converted to analog and then amplitude modulate 70 MHz quadrature carriers. The modulator outputs are summed, filtered, and buffered. A small amount of the energy out of the TWT (not shown in block diagrams) is coupled back to the transmitter where it is demodulated into I and Q baseband signals. The baseband signals are sampled and sent to a sign/magnitude comparator. The reference I and Q baseband generated by 8-bit D/A converters also go to the sign/magnitude converters.



The sign/magnitude converters generate a 1-bit error for each channel which is used to modify the transmitted I and Q words. This feedback arrangement is the basis for the adaptive predistortion technique.

### 3.3 M-QAM Demodulator

The M-QAM receiver shown in Figure 3.3 consists of four circuit boards: 1) receive analog card, 2) receive logic card, and 3,4) A/D converter board. The A/D converter board is a purchased item from TRW. Carrier and timing for the receivers are generated in the transmitter since there are no receiver timing or carrier recovery loops. Power is supplied from laboratory power supplies. Supply requirements are +5 V, -5.2 V, and +15 V.

Data and clock sinks from the receiver operate at TTL levels in 50 ohms and the 70 MHz IF input of 0 dBm into 50 ohms. Interfaces between the transmitter and receiver have been previously described in Paragraph 3.2.

Received 70 MHz IF is passed through an input attenuator and IF BPF Equalizer before being split for I and Q demodulation. The 70 MHz carrier from the transmitter is split into I and Q components before being used to demodulate the IF. The I and Q baseband go into 8-bit "flash" A/D converters where the I and Q baseband signals are converted to 8-bit words at symbol rate.

The I and Q words are sent to five word shift registers where the two most significant bits of the preceding and following words are used to form an 8-bit address to a RAM. The RAM output is a 12-bit correction word, the most significant eight bits of which are used to correct the center word in direction of the desired symbol word. The output of the correction adder addresses a raw decision PROM. The PROM output is three bits of symbol information plus a bit which tells whether the input address was above or below the symbol word. The single bit goes to a 12-bit adder where the 12-bit correction word is increased or decreased by one before being written

back into RAM. The 3-bit I and Q symbols plus the previous most significant I and Q bits are used to address a differential decoder. The differential decoder output goes to a parallel-to-serial converter where the 6-bit parallel word is converted to a serial data stream. The serial data goes to a 20-bit derandomizer where the original transmitted data stream is extracted. The received data and clock are buffered and presented to the receive data/clock sinks.



**Figure 3.3. Demodulator Block Diagram**

## 4.0 TEST RESULTS

The test program was performed at Harris GCSD facilities in Melbourne, Florida. Testing was performed with a 70 MHz loopback and through a simulated link which included a TWT. Filtering for FCC Docket 19311 was performed at 70 MHz rather than RF. The test plan which describes the test setups is included in this report as Appendix A.

### 4.1 Test Data

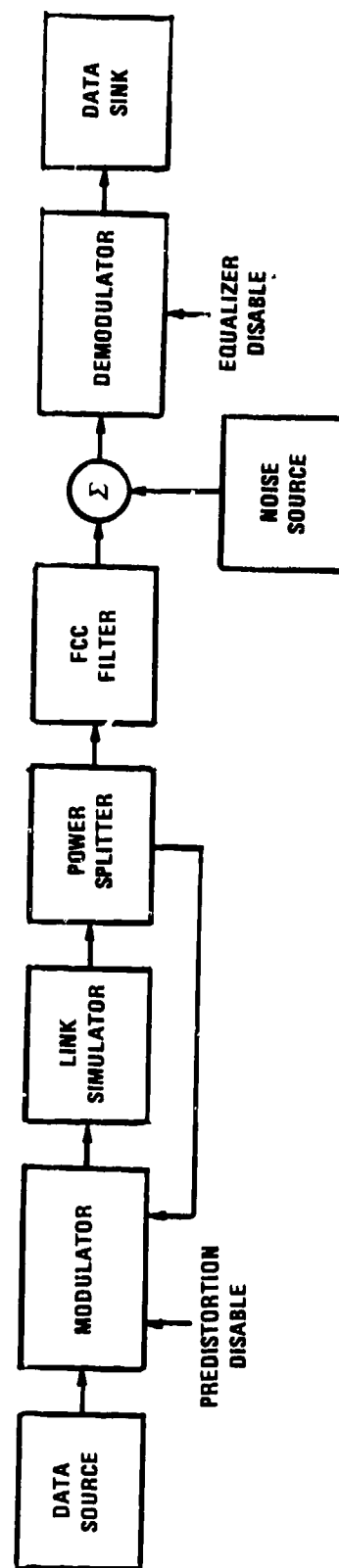
This paragraph presents data acquired at Harris GCSD during the period of mid-April 1981 through July 31, 1981.

#### 4.1.1 Spectrum Efficiency

The M-QAM breadboard is designed to operate with transmit filters that restrict the transmitted spectrum such that the requirements of FCC Docket 19311 are met. For this program, the FCC mask filter was designed at a center frequency of 70 MHz and used in the test setup shown in Figure 4.1.1-1. Response of the FCC mask filter is shown in Figure 4.1.1-2. The transmitted M-QAM spectrum before filtering is shown in Figures 4.1.1-3 and 4.1.1-4. The M-QAM spectrum after FCC mask filtering is shown in Figures 4.1.1-5 and 4.1.1-6, with the FCC mask superimposed. As can be seen, the filters used in the M-QAM breadboard provide sufficient rejection to meet the spectral requirements of FCC Docket 19311.

The FCC mask used on Figures 4.1.1-3 through 4.1.1-6 was generated by taking the transmitted power of -11.75 dBm as the 0 dB point on the FCC mask. Therefore, the 50 and 80 dB points of the FCC mask occur at -61.75 dBm and -91.75 dBm. However, since the spectrum analyzer IF bandwidth was 30 kHz, a correction factor of  $10 \log \left( \frac{30 \text{ kHz}}{4 \text{ kHz}} \right)$ , or 8.75 dB, must be applied so that the 50 and 80 dB points become -53 dBm and -83 dBm.





A1496-30

Figure 4.1.1.1-1. Simulated Link Test

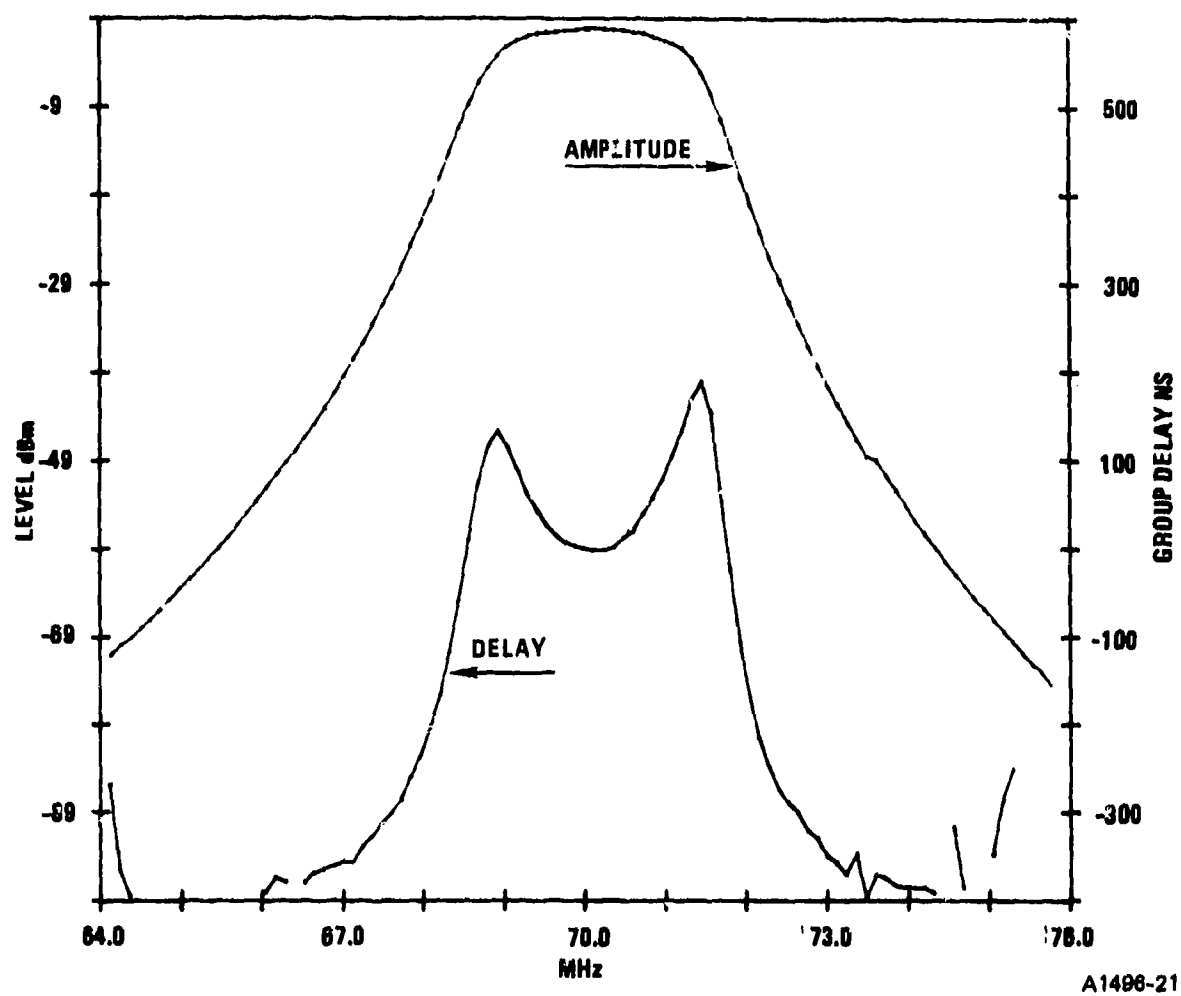
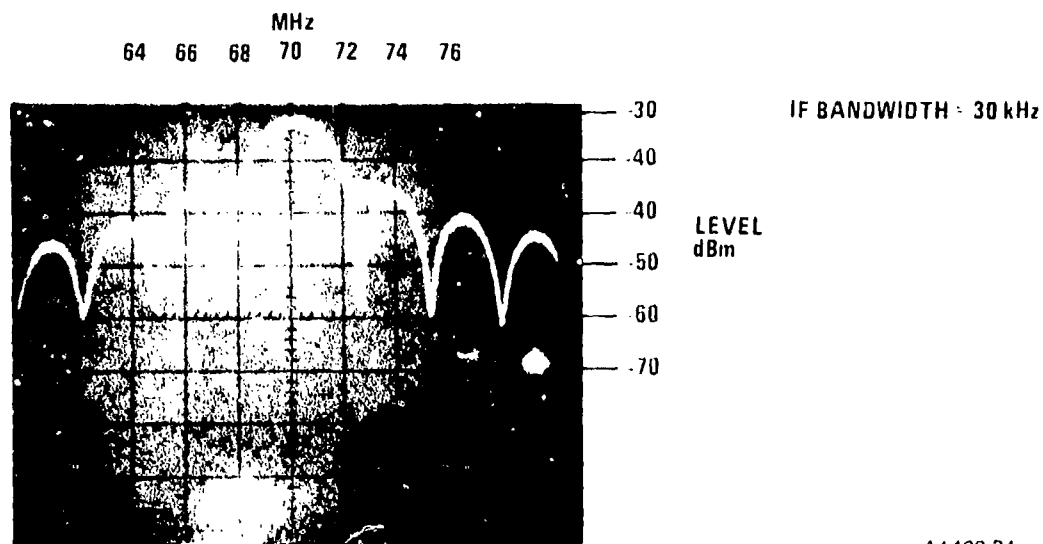
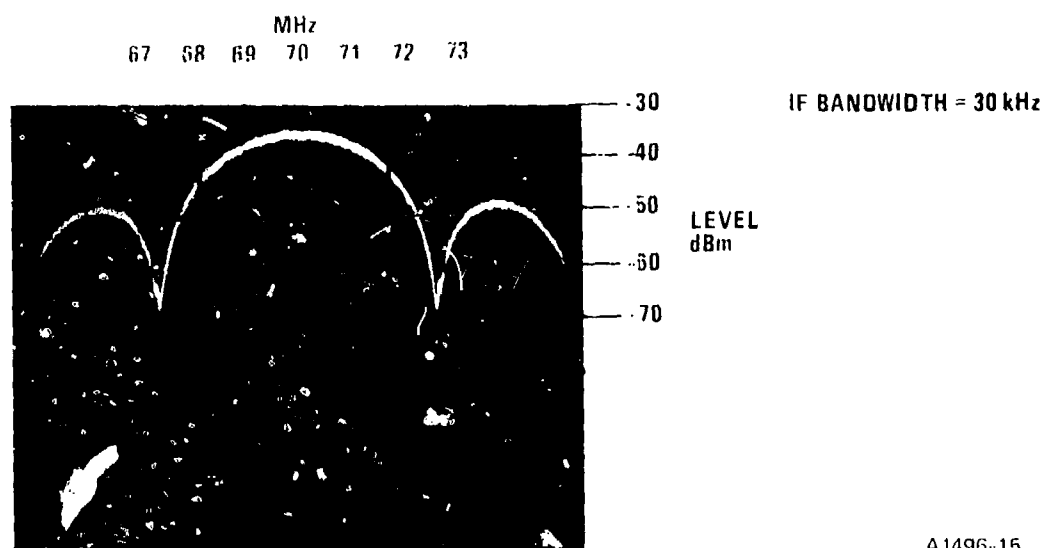


Figure 4.1.1-2. FCC Mask Filter Response



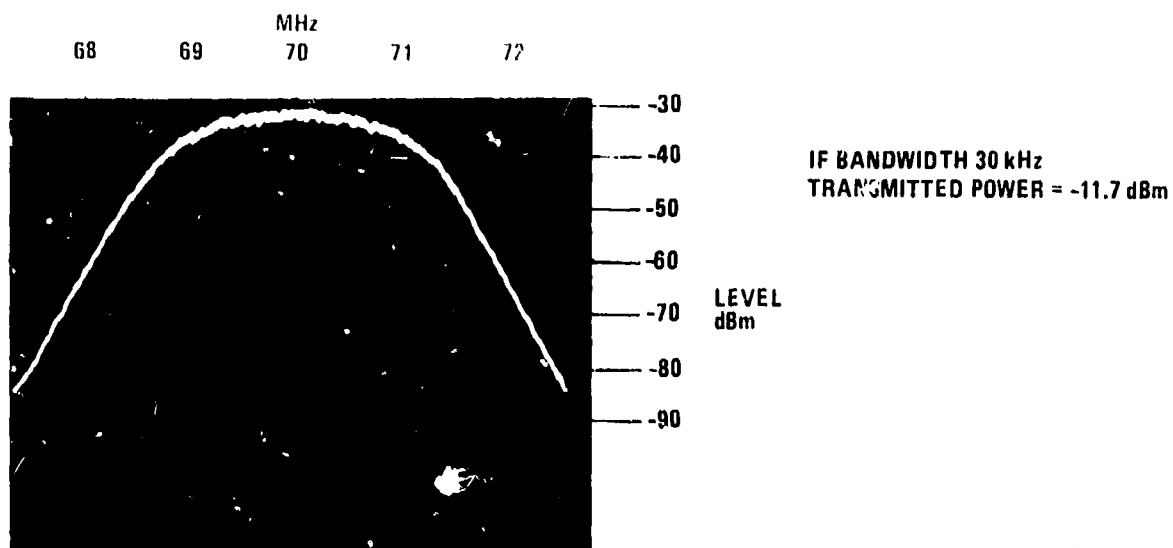
A1496-34

Figure 4.1.1-3. M-QAM Spectrum Before Filtering



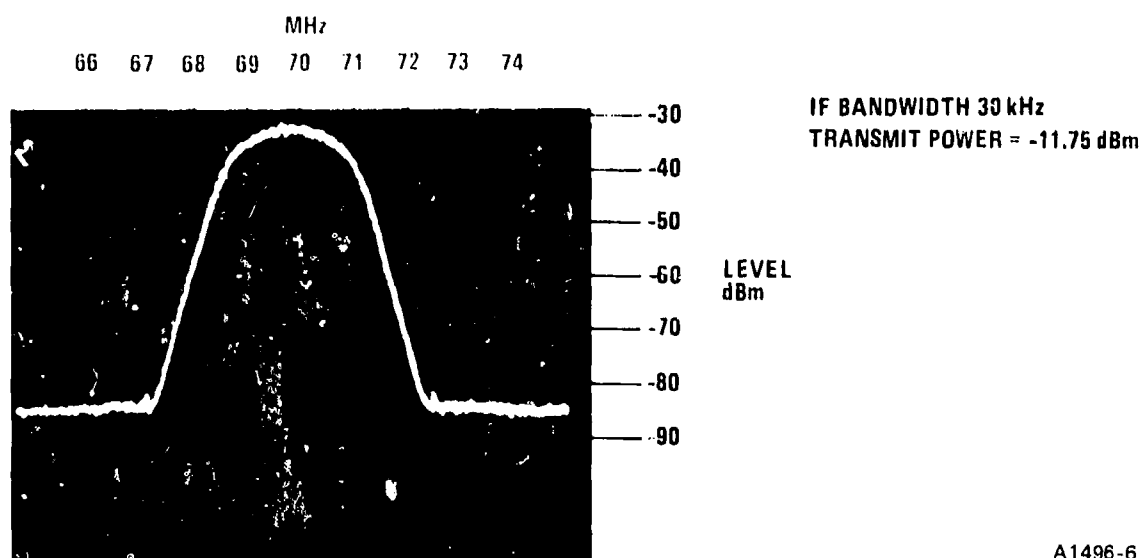
A1496-15

Figure 4.1.1-4. M-QAM Spectrum Before Filtering



A1496 33

Figure 4.1.1-5. M-QAM Spectrum After FCC Mask Filtering



A1496-6

Figure 4.1.1-6. M-QAM Spectrum After FCC Mask Filtering

#### 4.1.2 Predistortion

The predistortion loop is designed to remove the nonlinearities introduced by the TWT when it is operated near saturation. Figures 4.1.2-1 through 4.1.2-6 show the transmitted and received signal spaces for 4, 16, and 64-QAM when the predistortion loop is enabled or disabled, and the TWT is operated within 1 dB of saturation. Figure 4.1.2-1 presents 4-QAM with predistortion disabled, and where the top photograph is the signal space into the TWT and the bottom photograph is the received signal space. Figure 4.1.2-2 presents 4-QAM with predistortion enabled and where the top photograph is the signal space into the TWT and the bottom photograph is the received signal space. Figures 4.1.2-3 and 4.1.2-4 present 16-QAM, and Figures 4.1.2-5 and 4.1.2-6 present 64-QAM. The test setup used for taking this data is shown in Figure 4.1.1-1. The improvement provided by the predistortion loop is most evident in the 16 and 64-QAM cases.

#### 4.1.3 BER Versus $E_b/N_0$

The design objective for the Modem was a BER of  $1 \times 10^{-9}$  for  $E_b/N_0$  of 13.5, 19.5, and 22.5 dB when operating at 1.5, 3, and 4.5 b/s/Hz, respectively. As discussed in Section 2.0, these performance goals do not take into account the effects of the differential decoder or the self-synchronizing randomizer. The BER was measured in a variety of configurations as described below. Details of the test configurations are found in Appendix A.



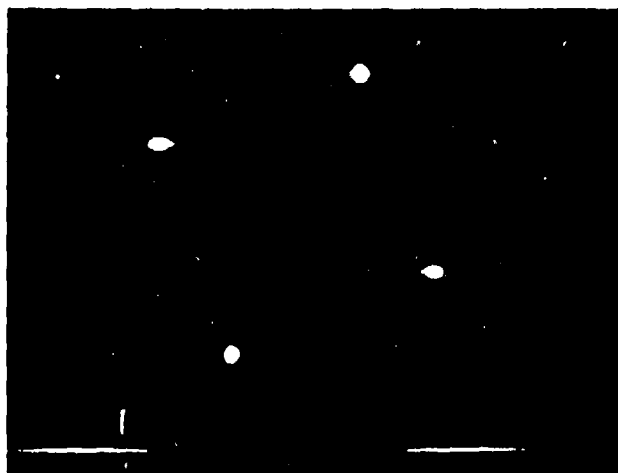
4 QAM SIGNAL SPACE INTO TWT



4 QAM SIGNAL SPACE AT RECEIVE

A1496-9

Figure 4.1.2-1. 4-QAM With Predistortion Disabled



4 QAM SIGNAL SPACE INTO TWI



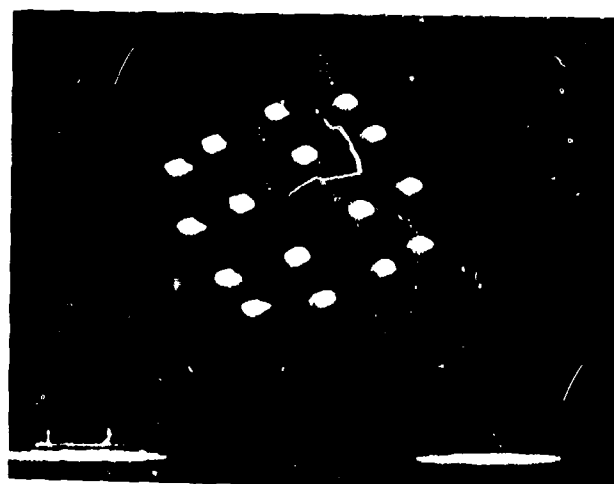
4 QAM SIGNAL SPACE AT RECEIVER

A1496-10

Figure 4.1.2-2. 4-QAM With Predistortion Enabled



16 QAM SIGNAL SPACE INTO TWT

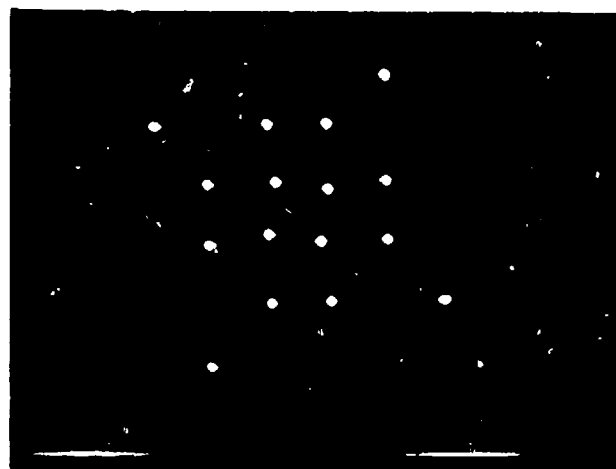


16 QAM SIGNAL SPACE AT RECEIVER

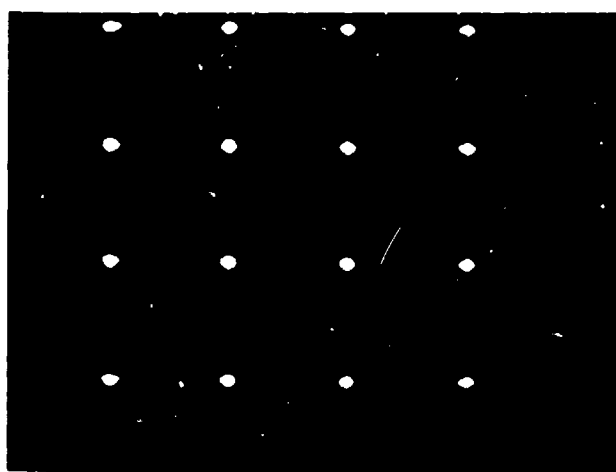
A1496-11

Figure 4.1.2-3. 16-QAM With Predistortion Disabled





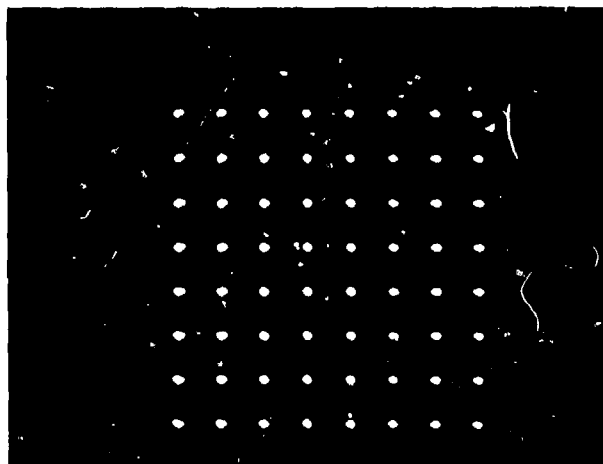
16 QAM SIGNAL SPACE INTO 1W1



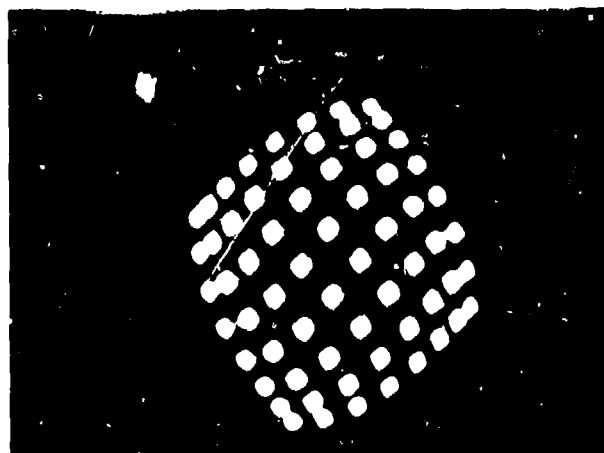
16 QAM SIGNAL SPACE AT RECEIVER

A1496-12

Figure 4.1.2-4. 16-QAM With Predistortion Enabled



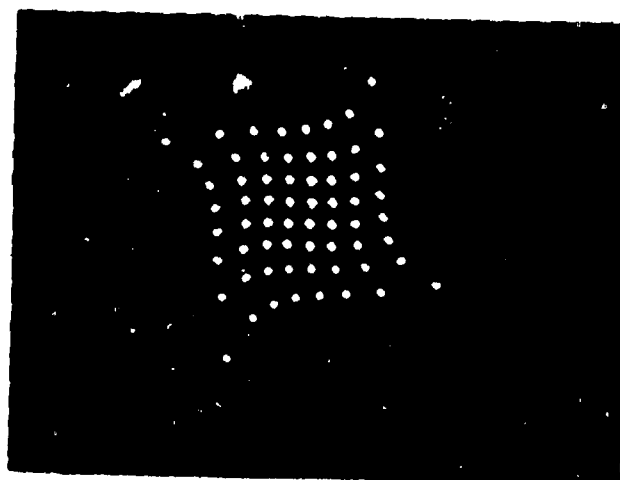
64 QAM SIGNAL SPACE INTO TWT



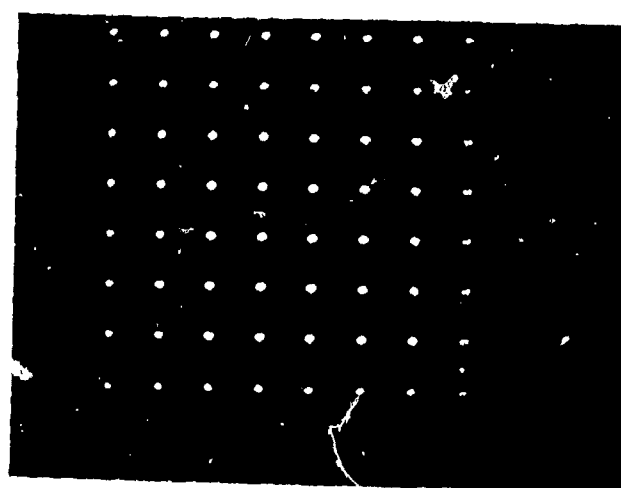
64 QAM SIGNAL SPACE AT RECEIVER

A1496-13

Figure 4.1.2-5. 64-QAM With Predistortion Disabled



64 QAM SIGNAL SPACE INTO TWT



64 QAM SIGNAL SPACE AT RECEIVER

A1496-14

Figure 4.1.2-6. 64-QAM With Predistortion Enabled

#### 4.1.3.1 Baseline Performance

In order to obtain baseline performance data, the Modem was first run back-to-back without the FCC mask and receive filters. Since the noise would be unrestricted by a receive filter, the performance curve would be expected to be substantially away from predicted curves. Therefore, a correction factor was derived for application to the data. Since<sup>6</sup>

$$\frac{E_b}{N_0} = \frac{S}{N} - 10 \log \left( \frac{\text{BIT RATE}}{\text{NOISE BW}} \right) \quad 4.1.3.1-1$$

where  $\frac{S}{N}$  is the measured signal-to-noise ratio and an ideal filter would have a bandwidth equal to the symbol rate, we have

$$\frac{E_b}{N_0} = \frac{S}{N} - 10 \log \left( \frac{\text{BIT RATE}}{\text{NOISE BW}} \right) - 10 \log \frac{\text{NOISE BW}}{\text{SYMBOL RATE}} \quad 4.1.3.1-2$$

which reduces to

$$\frac{E_b}{N_0} = \frac{S}{N} - 10 \log \left( \frac{\text{BIT RATE}}{\text{SYMBOL RATE}} \right) \quad 4.1.3.1-3$$

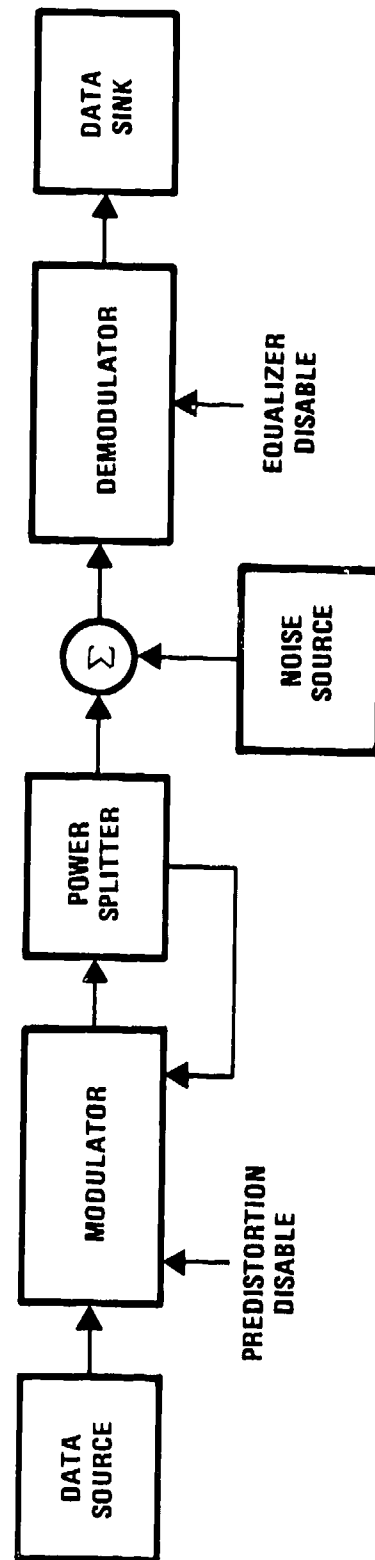
but BIT RATE = N X SYMBOL RATE, where N is the number of bits/symbol, and

$$\frac{E_b}{N_0} = \frac{S}{N} - 10 \log N, \quad N = 2, 4, 6 \quad 4.1.3.1-4$$

which is the factor applied to the data.

Figure 4.1.3.1-1 shows the test setup for performing back-to-back testing without filters and Figures 4.1.3.1-2 through 4.1.3.1-4 give the performance results for that setup. Note that QPSK (4-QAM) falls on the ideal curve while 16-QAM is within 0.5 dB of ideal and 64-QAM is within 1 dB of ideal. Figure 4.1.3.1-5 shows the test setup for performing simulated link testing without filters and Figures 4.1.3.1-6 through 4.1.3.1-8 give the performance results for that setup. As before, QPSK (4-QAM) falls on the ideal curve and 16-QAM is within 0.5 dB of the curve. The degraded performance for 64-QAM, when going through the TWT and link simulator, is caused by simulator output noise. The noise power out of the simulator with no FCC mask filter was measured at -45.5 dBm, while the noise power required for an  $E_b/N_0 = 25$  dB was -45.2 dBm. Summing these two noise powers gives an effective noise power of -42.4 dBm which equates to an  $E_b/N_0 = 22.2$  dB. The dashed performance curve in Figure 4.1.3.1-8 represents the performance when the additional noise is taken into account. As can be seen, the performance curve is within 1 dB of ideal. Therefore, the introduction of the link simulator and TWT caused no significant degradation in performance.

Figures 4.1.3.1-9 through 4.1.3.1-11 show the performance for M-QAM through the link simulator and TWT, with no filter, when the predistortion loop is disabled and the TWT is operated within 1 dB of saturation. QPSK (4-QAM) moves away from ideal by nearly a dB while 16-QAM moves nearly 6 dB from ideal. The 64-QAM mode could perform no better than a BER of  $2.5 \times 10^{-2}$ . Thus, there is significant degradation in performance when the TWT is operated near saturation with no predistortion.



A1496-27

Figure 4.1.3.1-1. Test Setup for Back-to-Back Test Without Filters

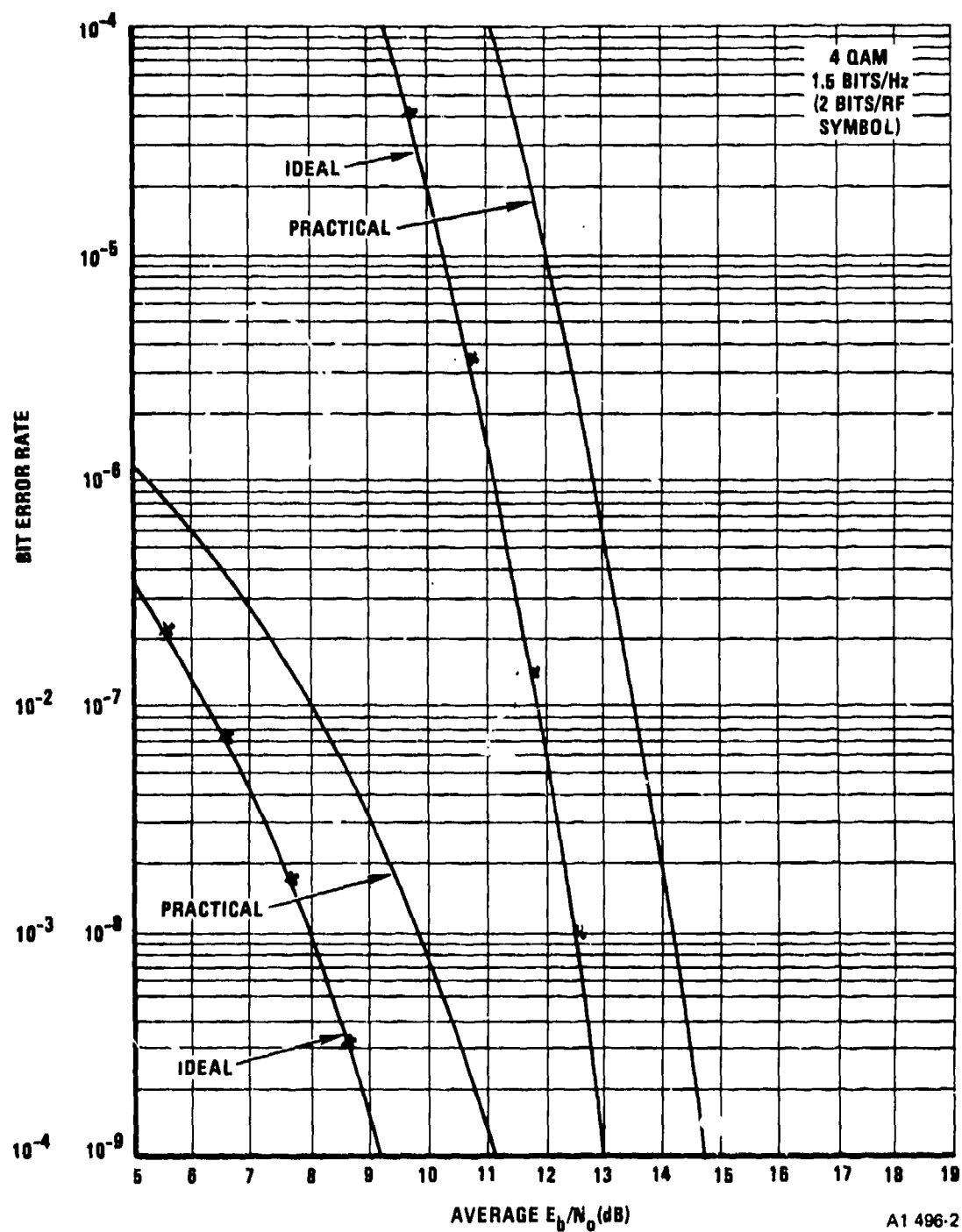


Figure 4.1.3.1-2. 4-QAM Back-to-Back Performance, No Filters

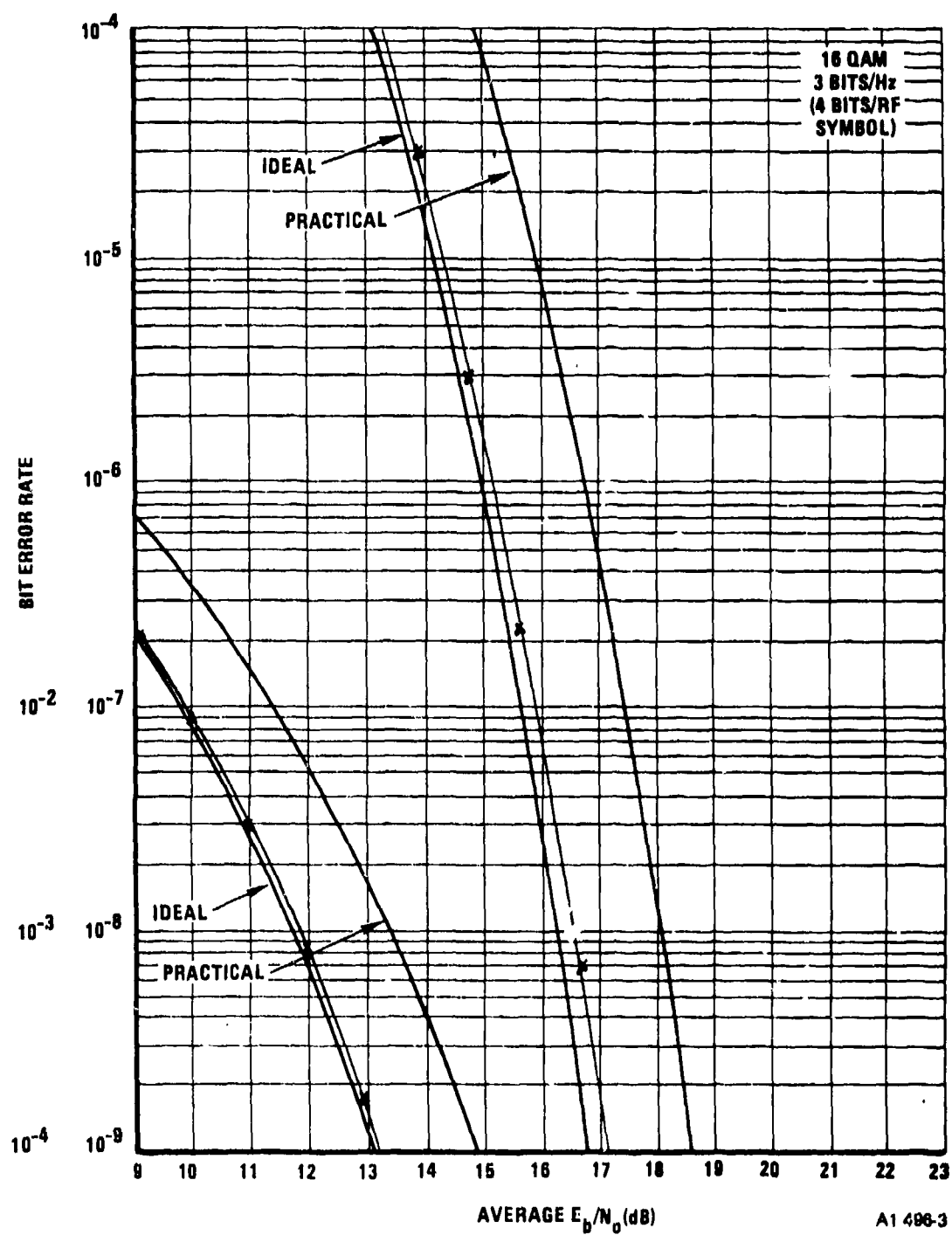


Figure 4.1.3.1-3. 16-QAM Back-to-Back Performance, No Filters



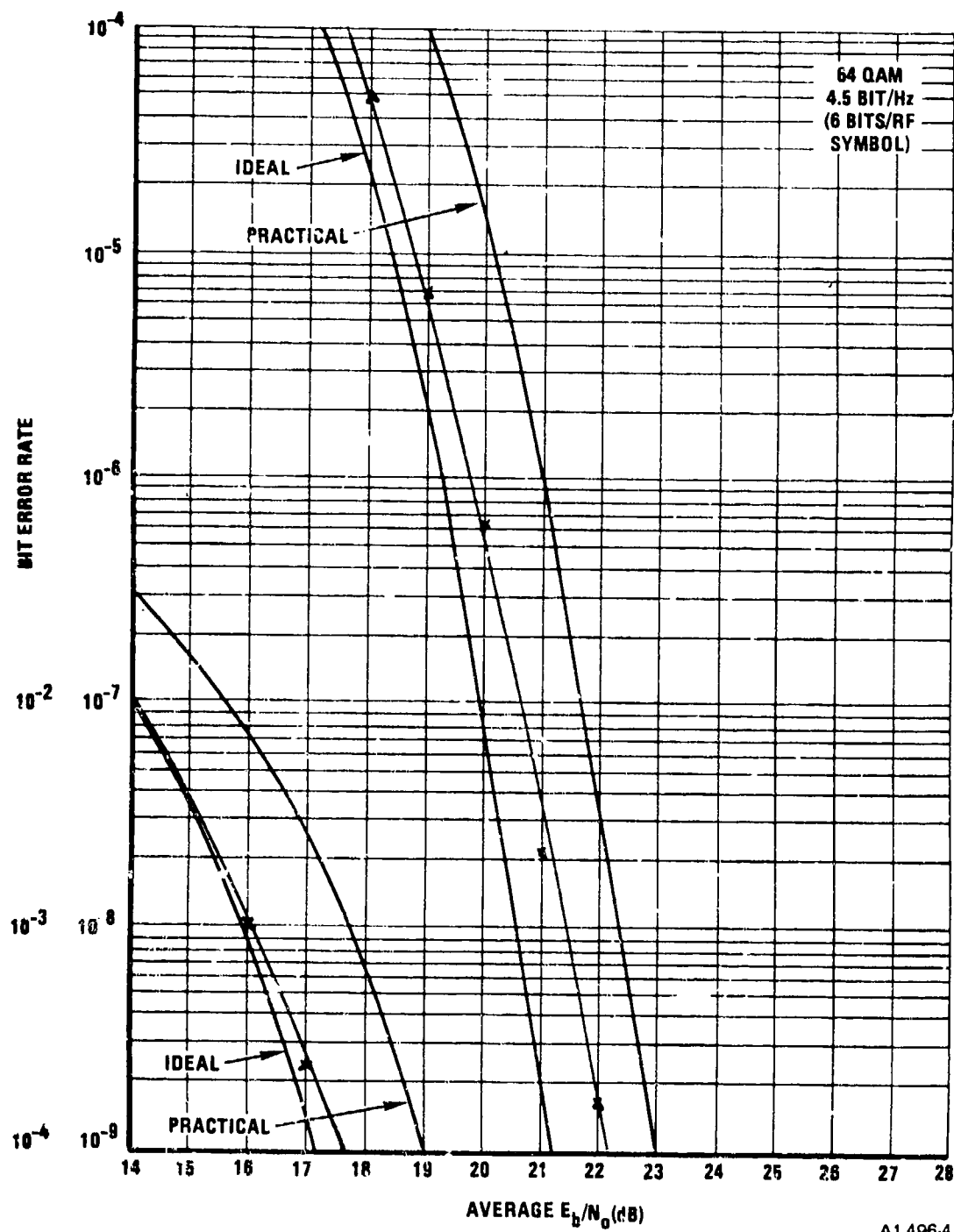
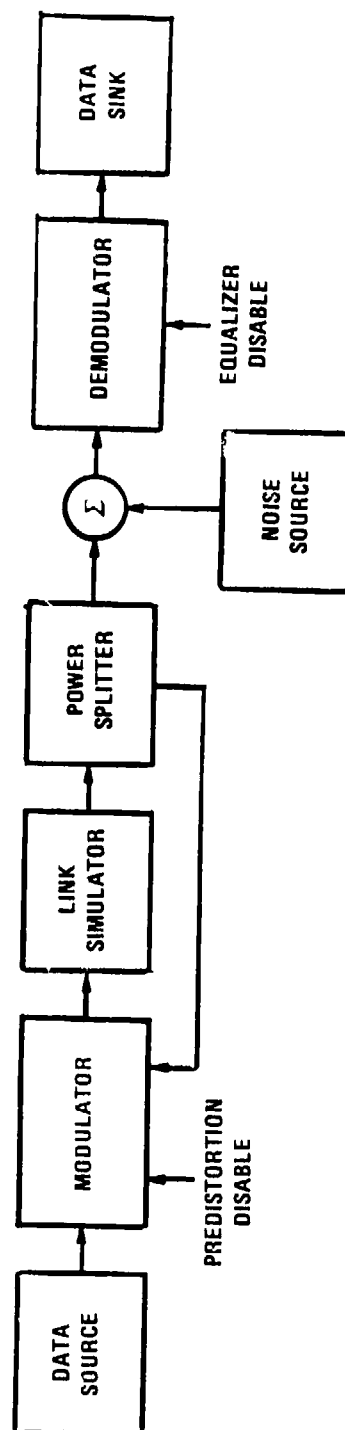


Figure 4.1.3.1-4. 64-QAM Back-to-Back Performance, No Filters



A1 496-30-1

Figure 4.1.3.1-5. Simulated Link Test Without Filters

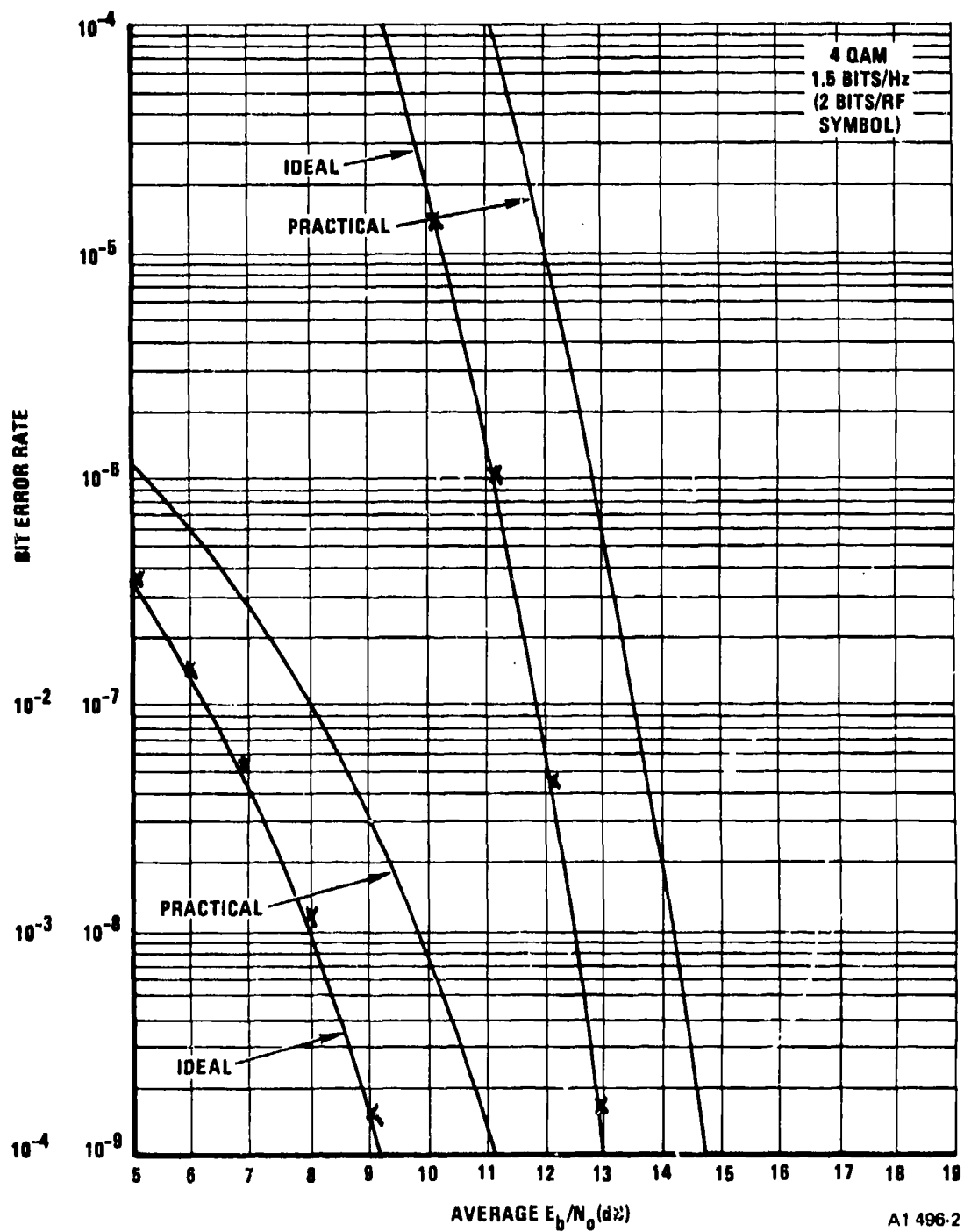


Figure 4.1.3.1-6. 4-QAM Performance Through the Link Simulator, No Filters

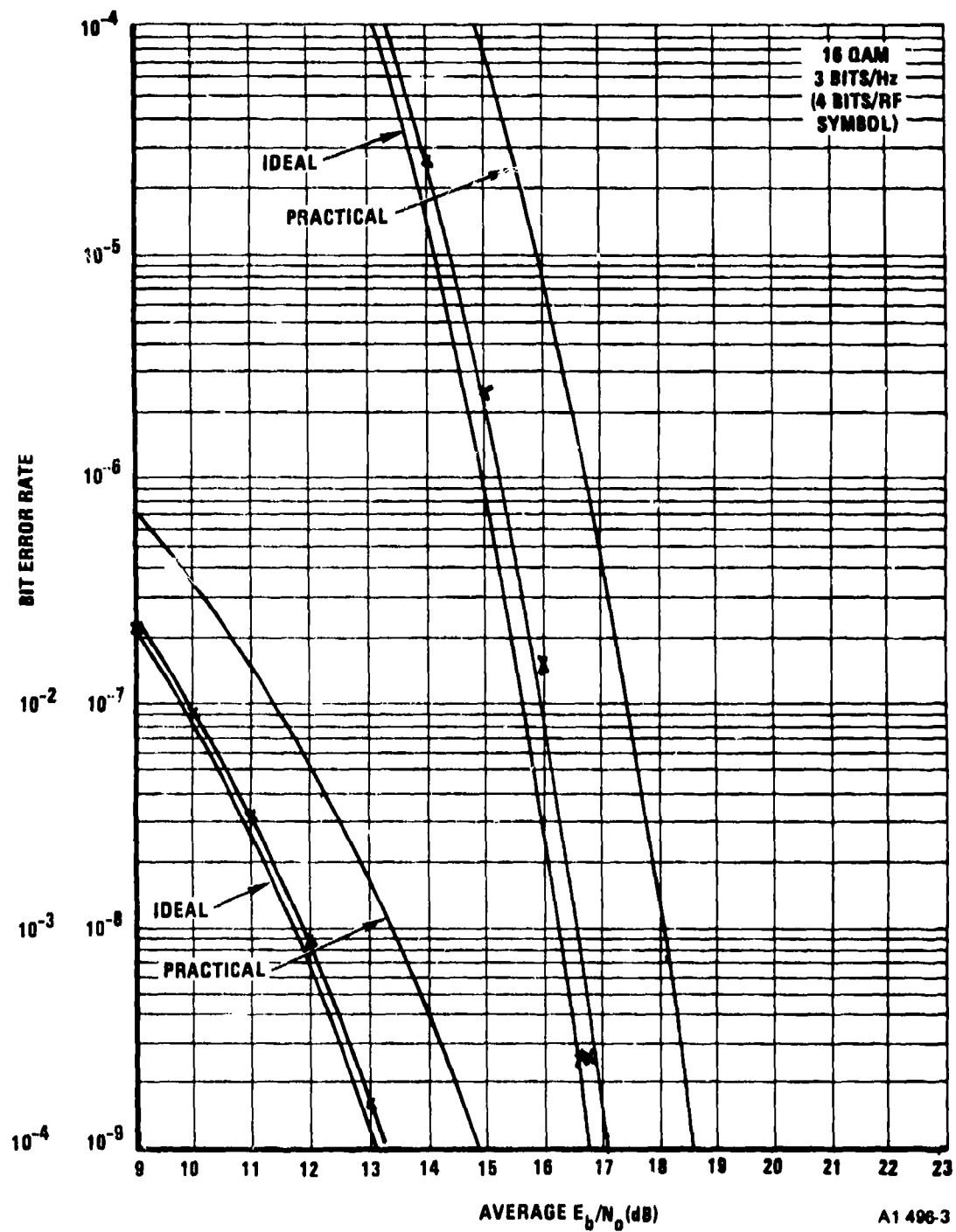


Figure 4.1.3.1-7. 16-QAM Performance Through the Link Simulator, No Filters

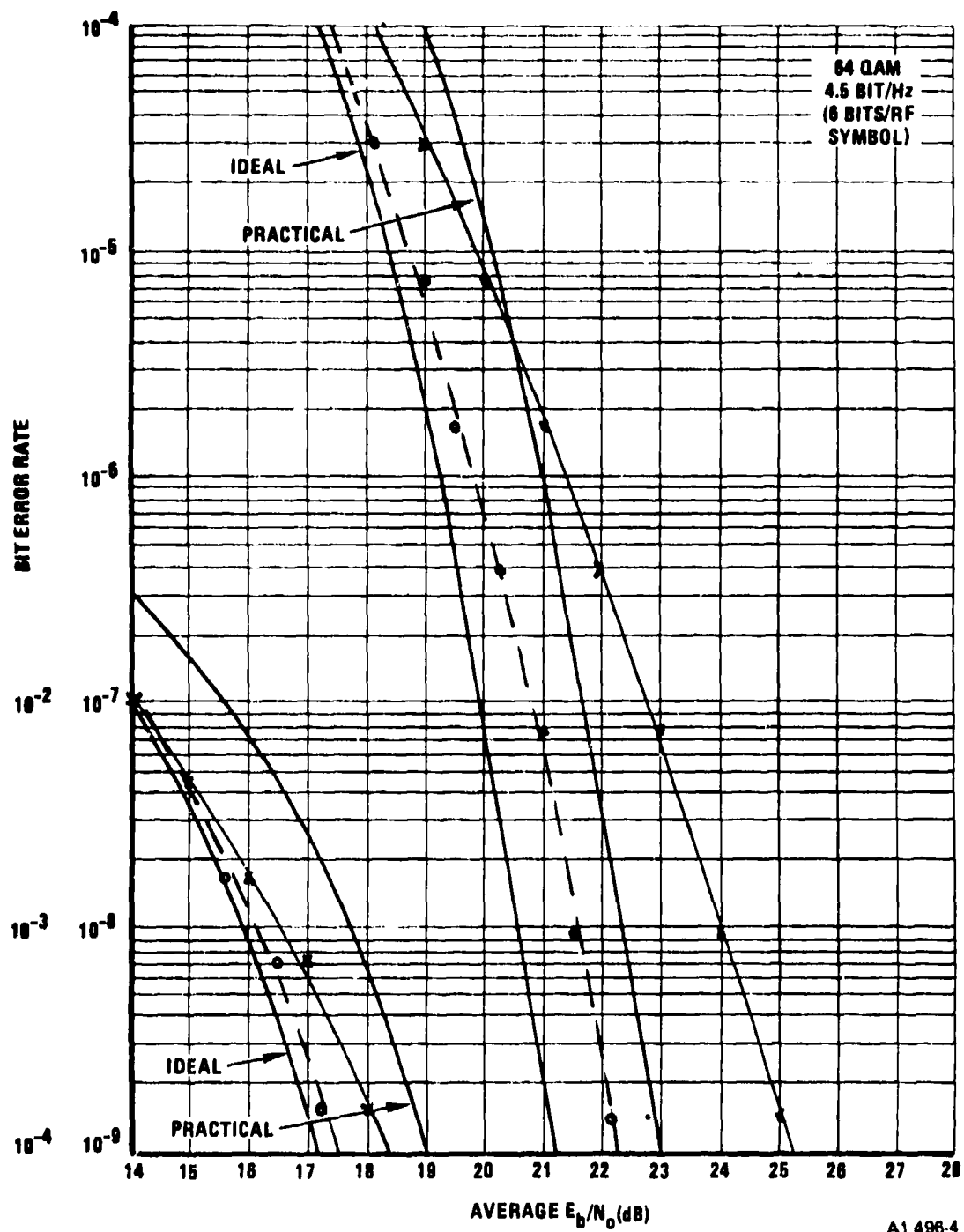


Figure 4.1.3.1-8. 64-QAM Performance Through the Link Simulator, No Filters

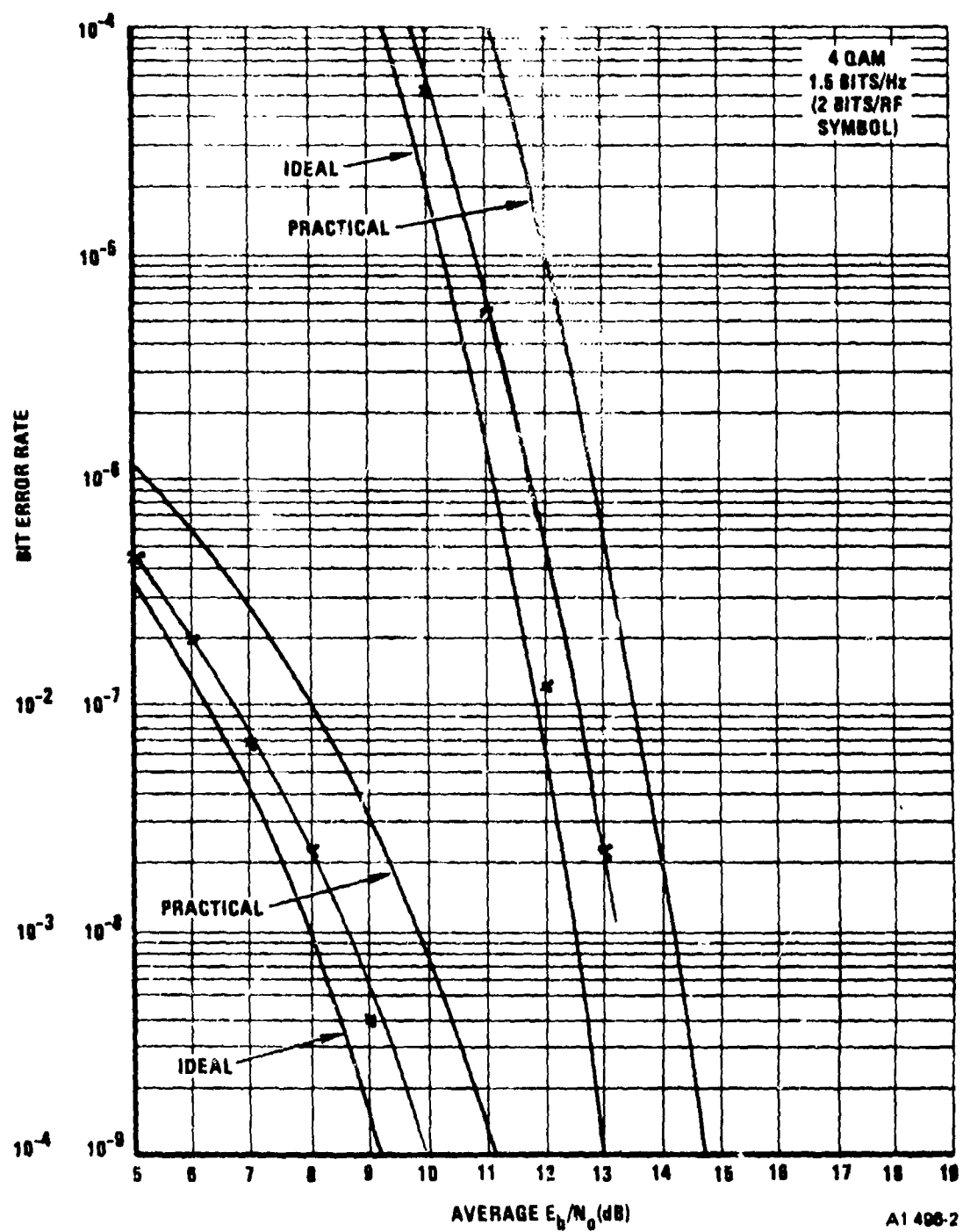


Figure 4.1.3.1-9. 4-QAM Performance Through the Link Simulator With Predistortion Disabled

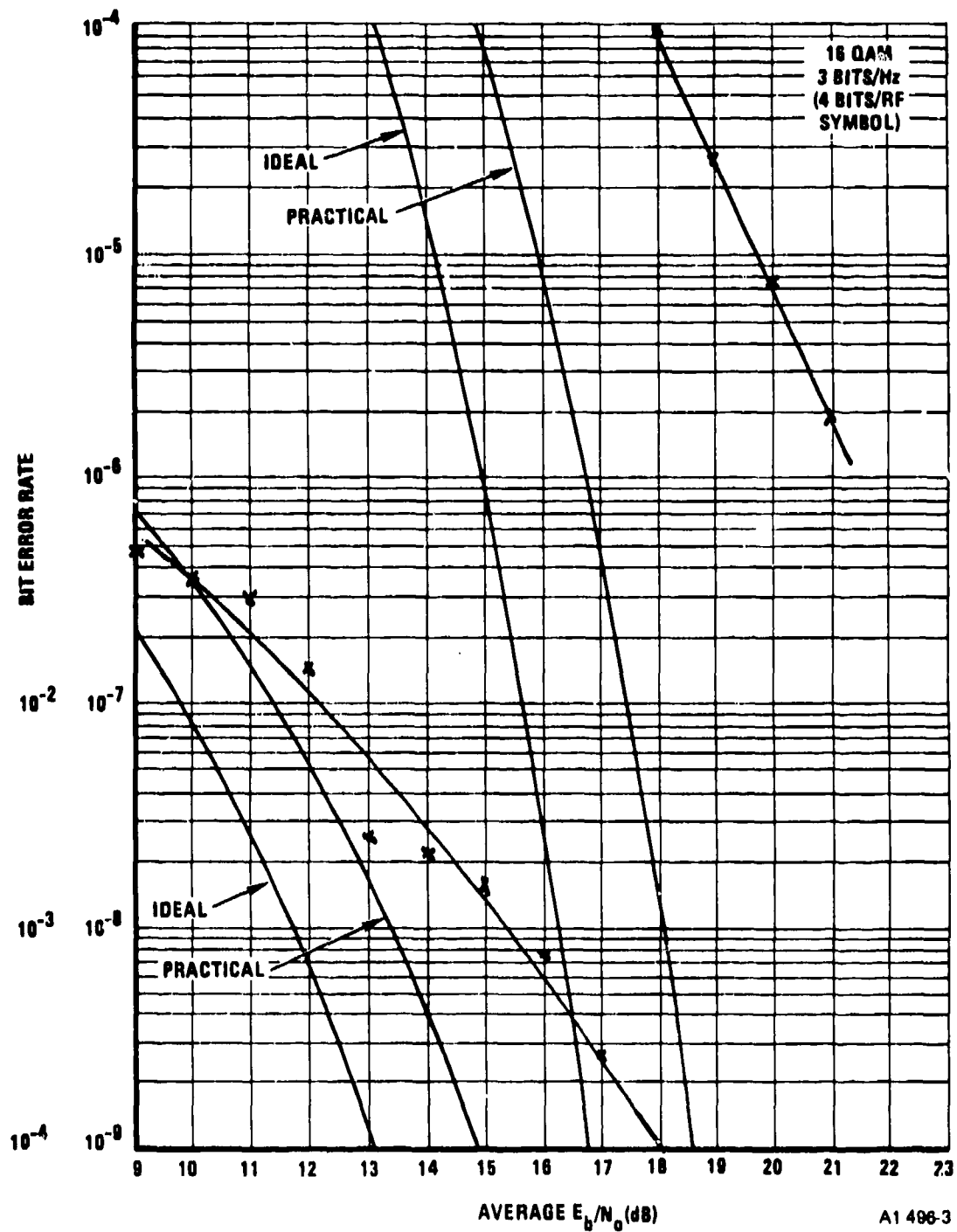


Figure 4.1.3.1-10. 16-QAM Performance Through the Link Simulator With Predistortion Disabled

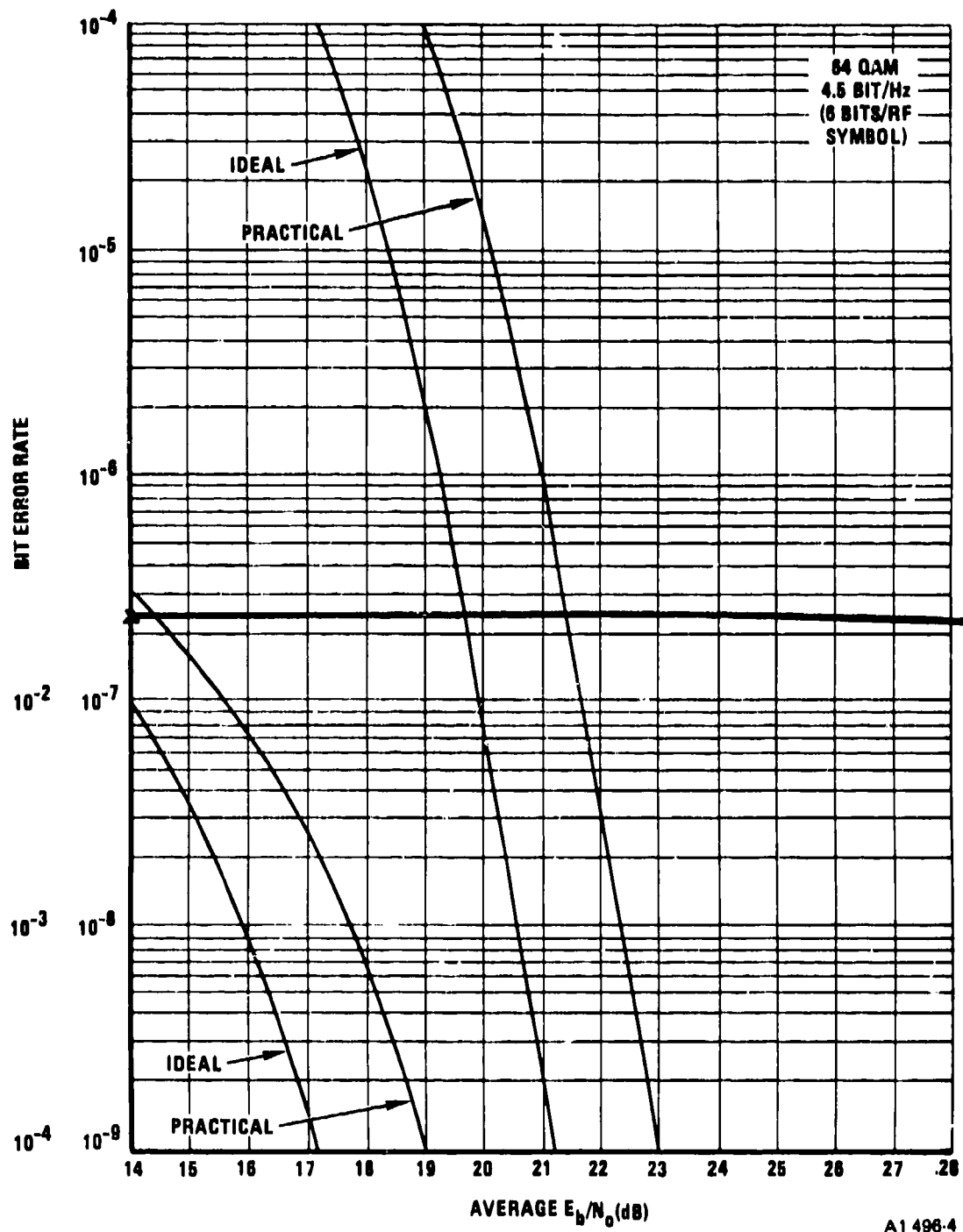


Figure 4.1.3.1-11. 64-QAM Performance Through the Link Simulator With Predistortion Disabled



#### 4.1.3.2 Preliminary Test Results

During the checkout and debug phase of the program, the mask filter had the response shown in Figure 4.1.3.2-1. As seen in Figure 4.1.3.2-2, this version of the mask filter did not entirely satisfy the FCC requirements. The receive filter response is shown in Figure 4.1.3.2-3, and the composite mask and receive filter response after equalization is shown in Figure 4.1.3.2-4. Figure 4.1.3.2-4 also shows, for comparison, the response used in the TWT simulations. The combination of receive filter and equalizer had a measured noise bandwidth of 3.31 MHz.

Figures 4.1.3.2-5 through 4.1.3.2-7 present the performance for a back-to-back configuration at 70 MHz with only the receive filter inserted.  $E_b/N_0$  was calculated using equation 4.1.3.1-1, where the noise bandwidth of the input noise was 31.24 MHz. The next set of curves, presented in Figures 4.1.3.2-8 through 4.1.3.2-10, represent the performance when the mask filter, receive filter, and equalizer are in place in a back-to-back configuration at 70 MHz. Note the performance improvement over the previous curves.

Figures 4.1.3.2-11 through 4.1.3.2-13 were obtained by first adjusting the receive level for a minimum error count when in a back-to-back mode with all filters. It is evident that receive level is a critical parameter affecting error performance in this system.

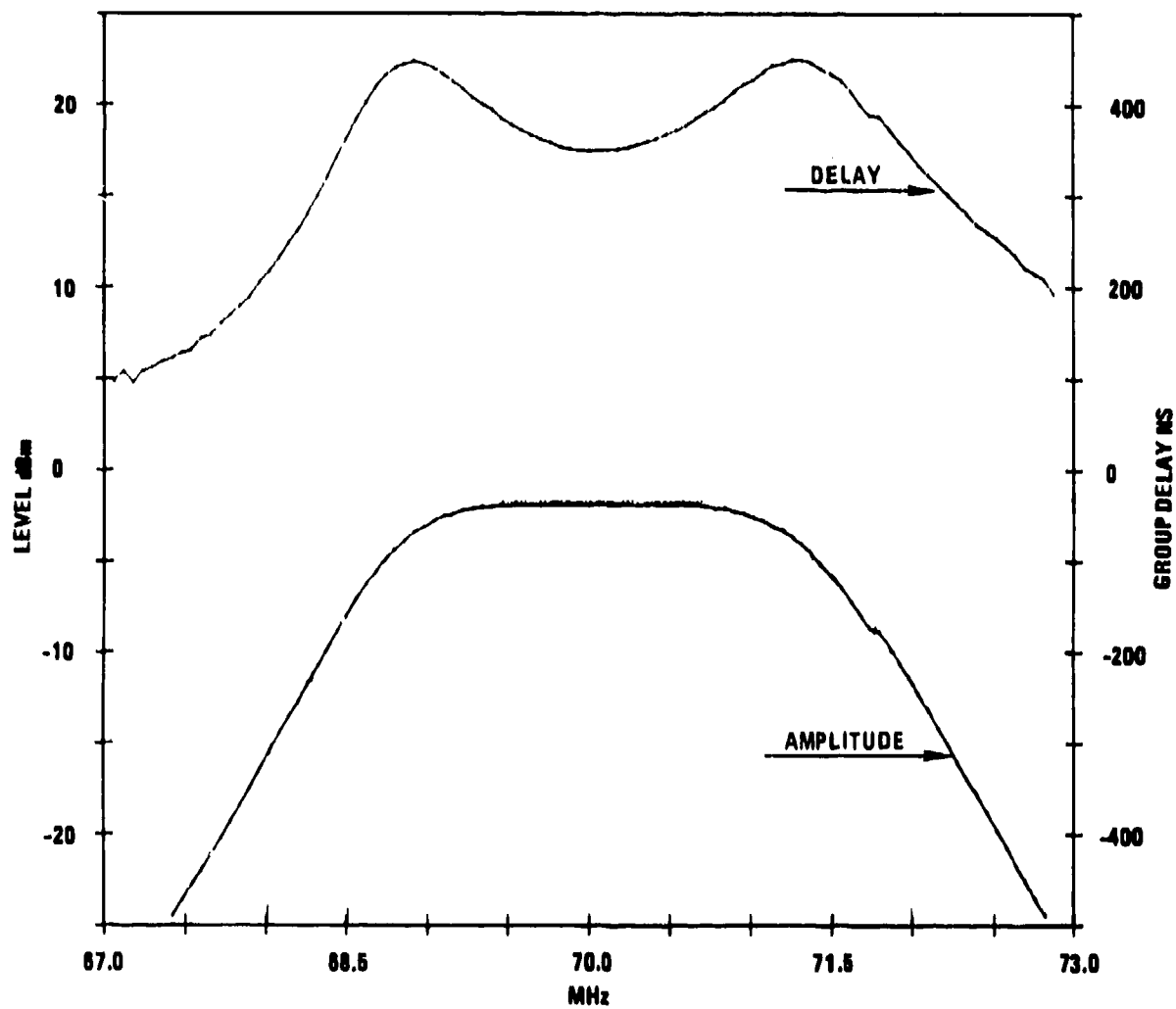
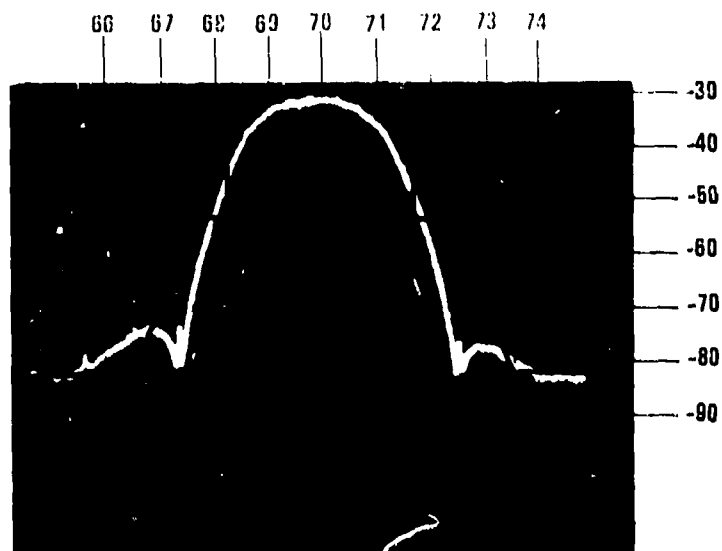
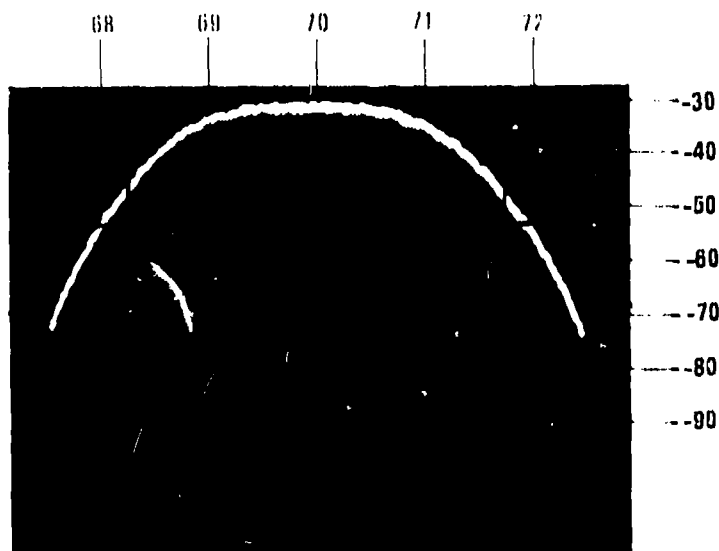


Figure 4.1.3.2-1. Preliminary Mask Filter Response



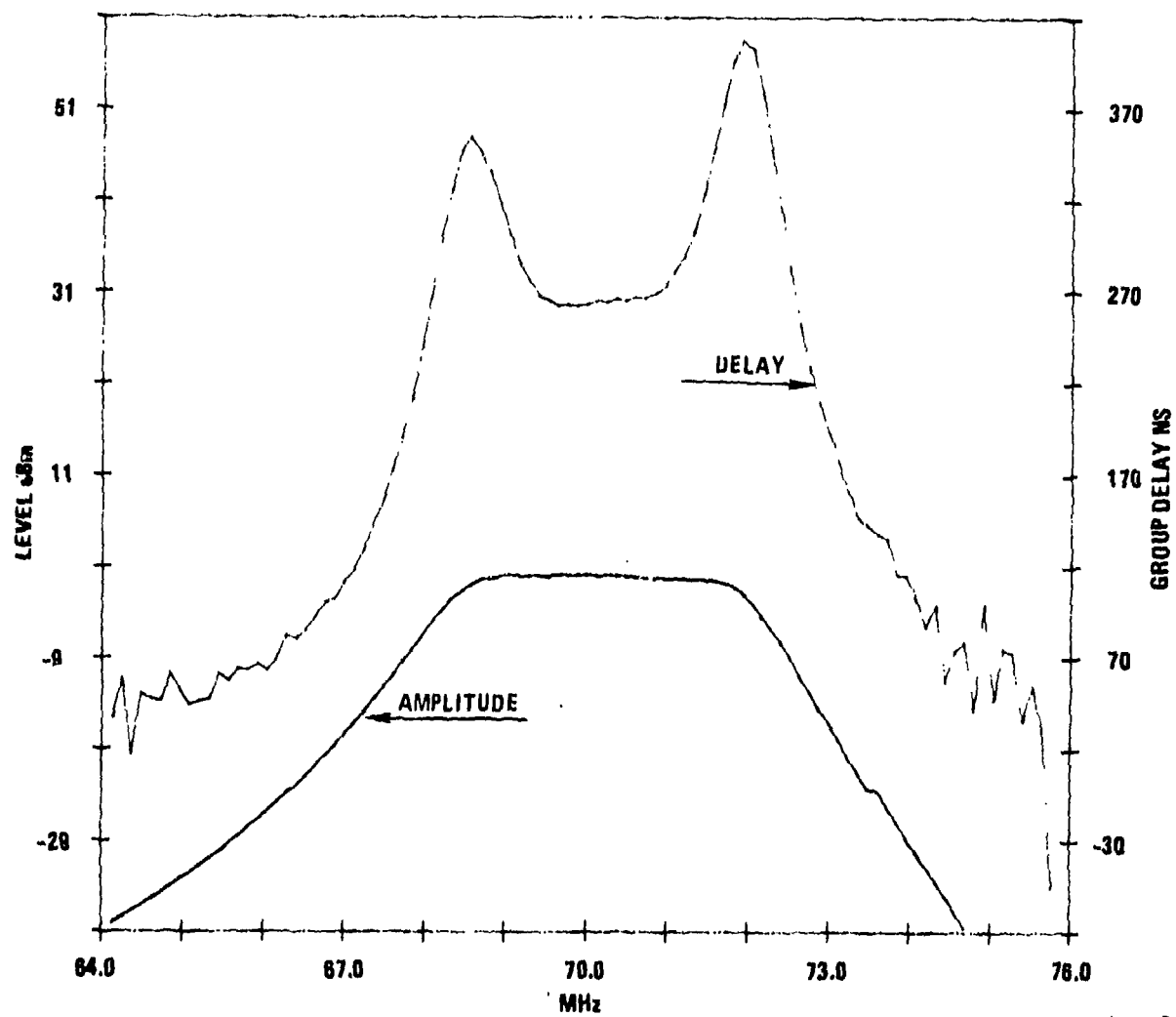
1 MHz/DIV  
30 kHz/VIDEO  
INPUT - 11.50



,5 MHz/DIV  
30 kHz VIDEO

A1496-5

Figure 4.1.3.2-2. Preliminary Mask Filter Rejection



A1496-18

Figure 4.1.3.2-3. Preliminary M-QAM Receive Filter

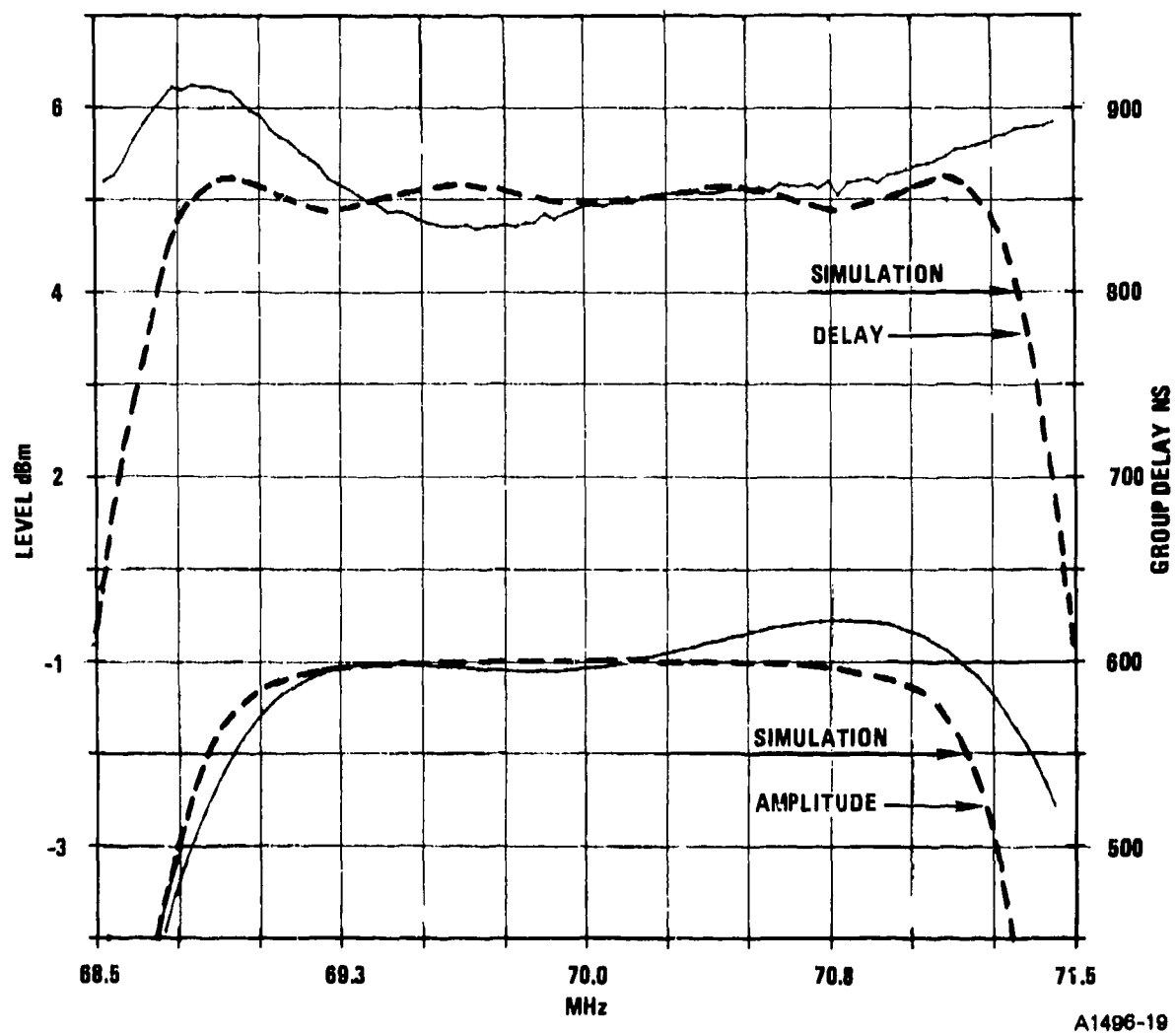


Figure 4.1.3.2-4. Preliminary Cascaded Response

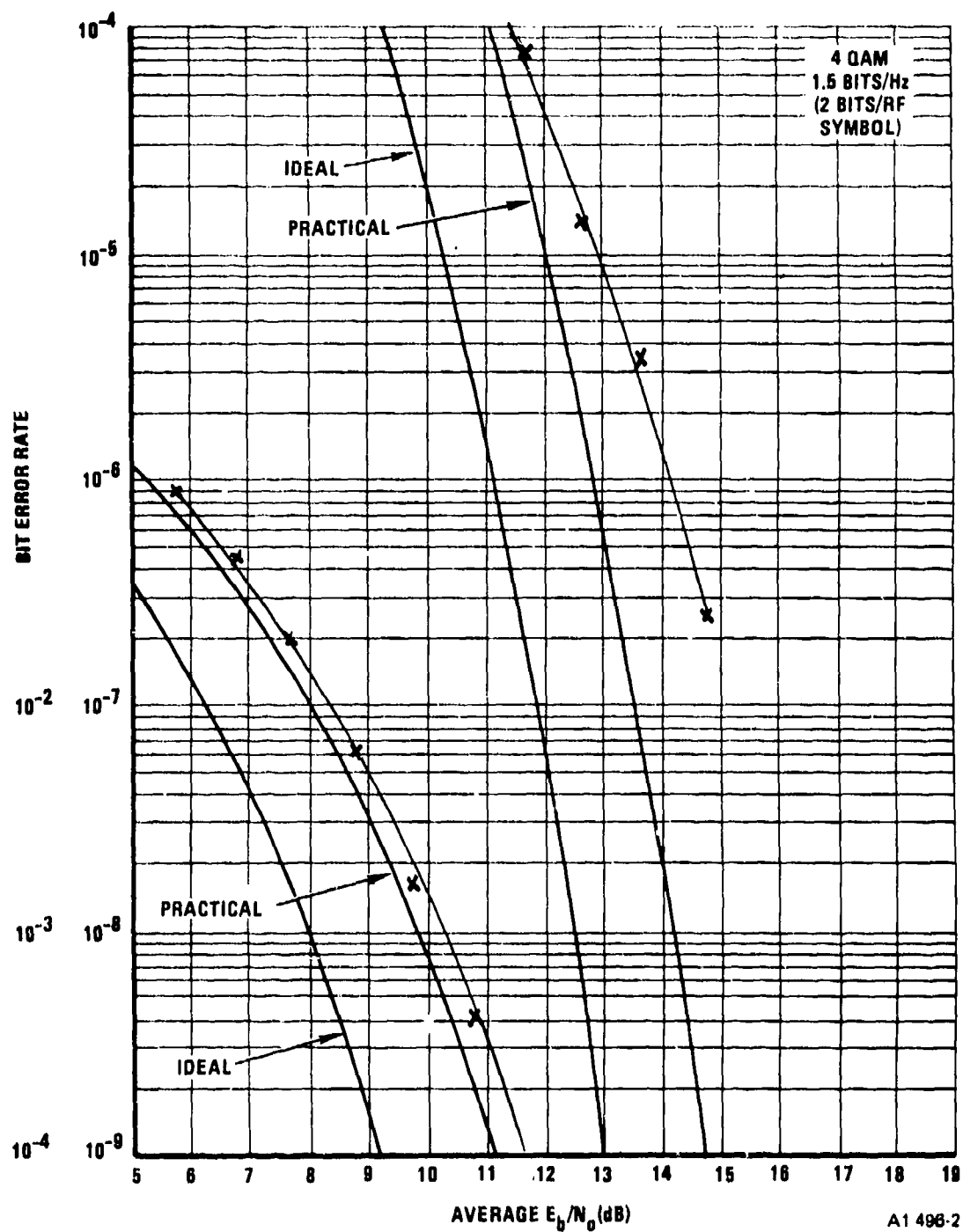


Figure 4.1.3.2-5. 4-QAM Back-to-Back Performance With Receive Filter

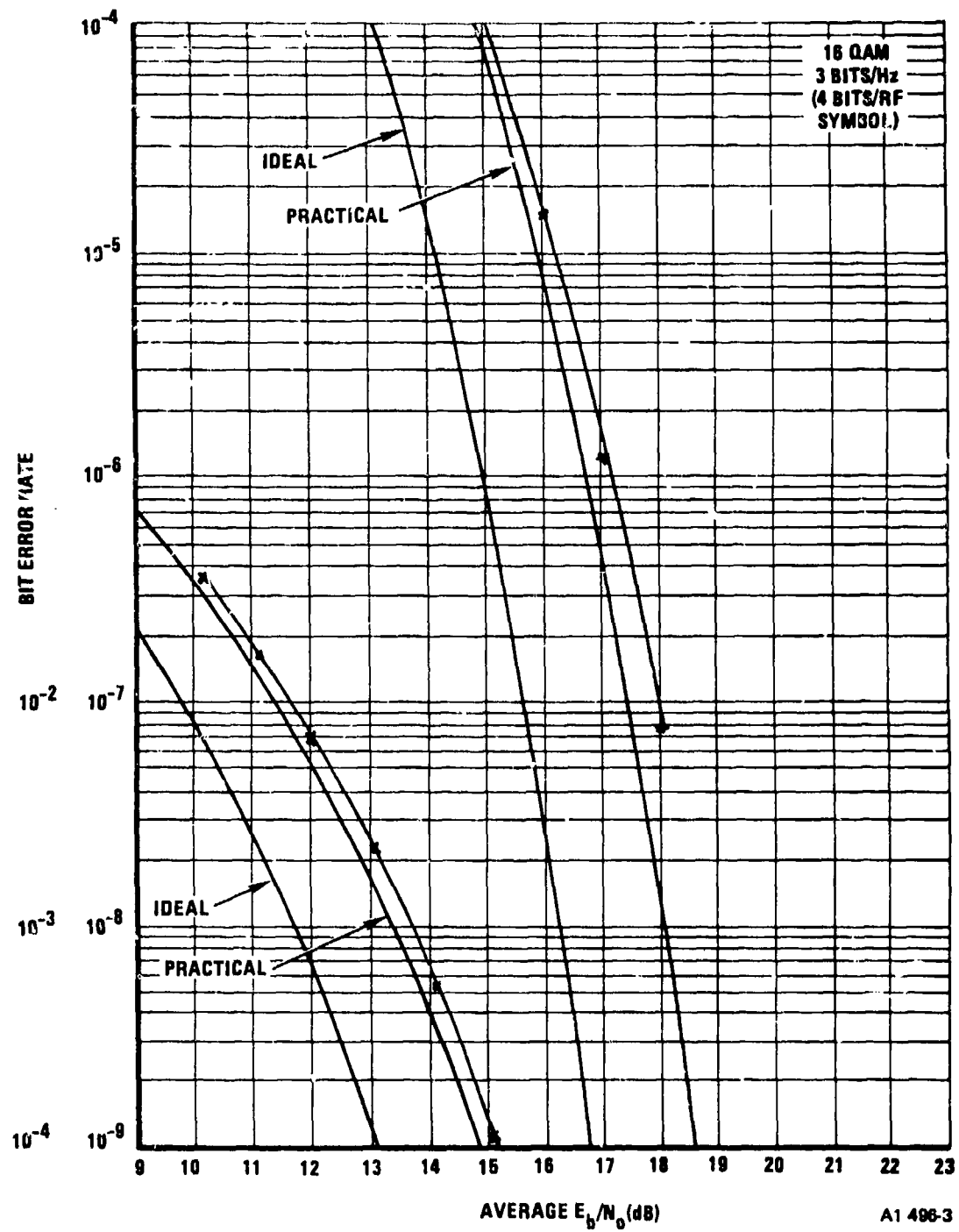


Figure 4.1.3.2-6. 16-QAM Back-to-Back Performance With Receive Filter

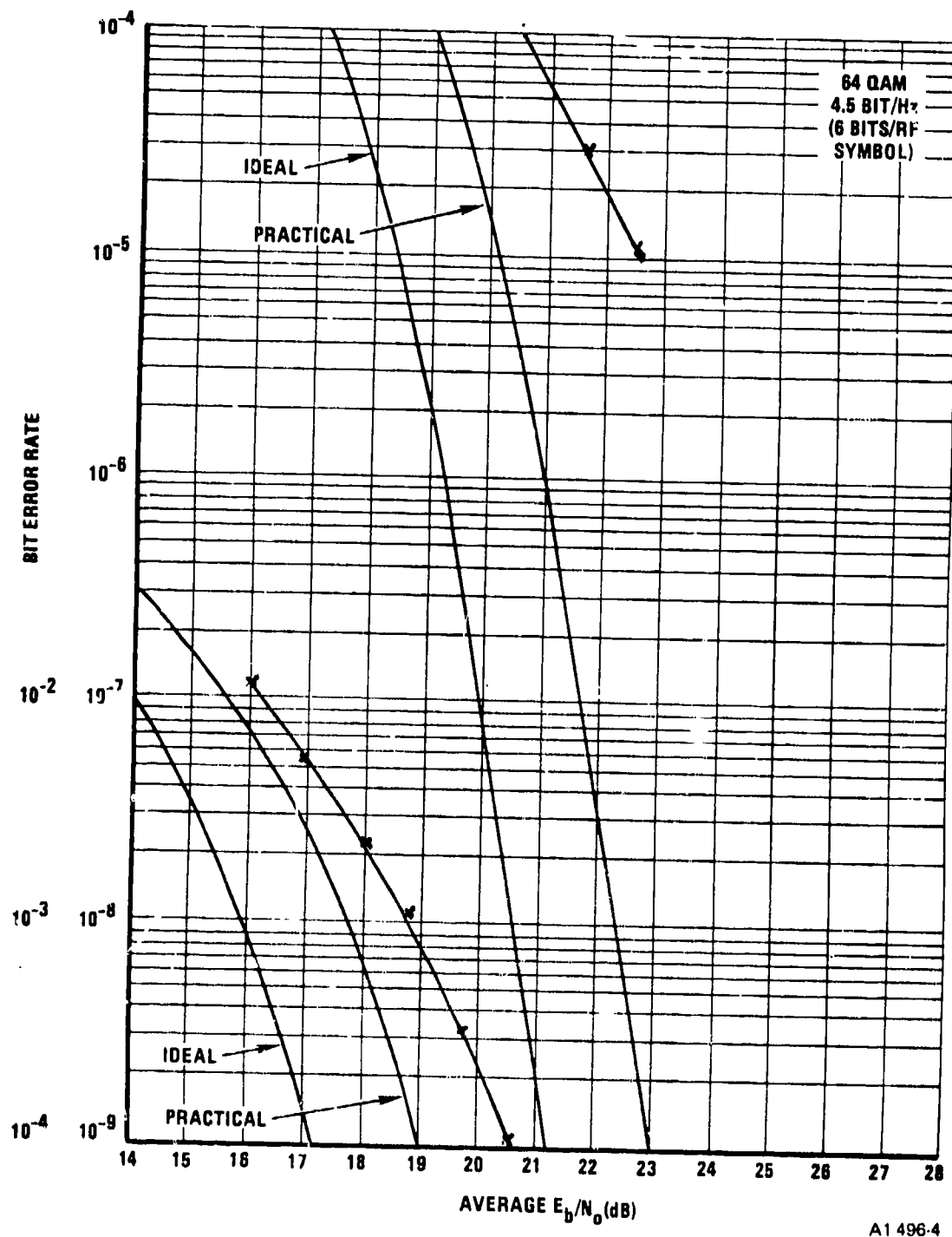


Figure 4.1.3.2-7. 64-QAM Back-to-Back Performance With Receive Filter



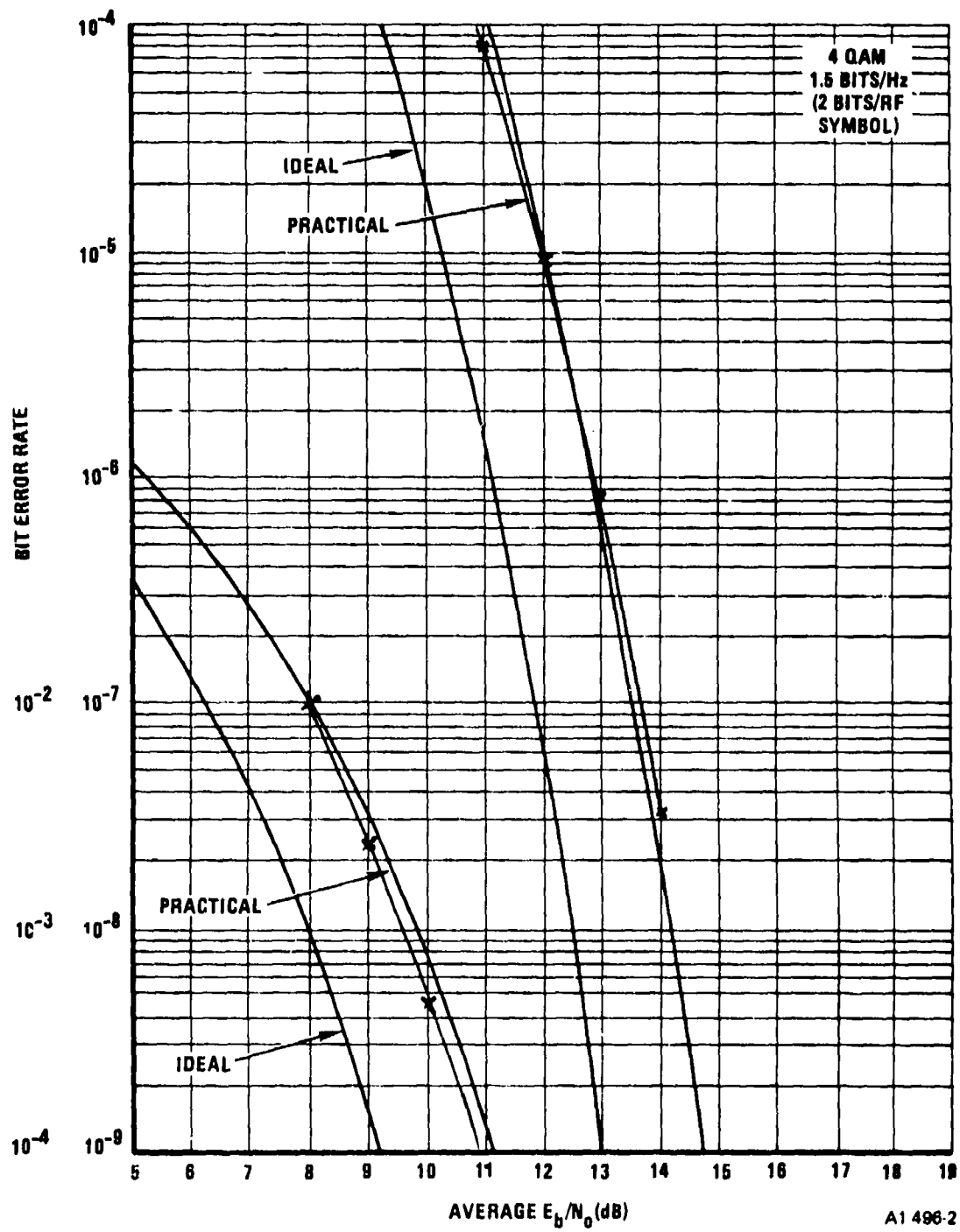


Figure 4.1.3.2-8. 4-QAM Back-to-Back Performance With All Filters

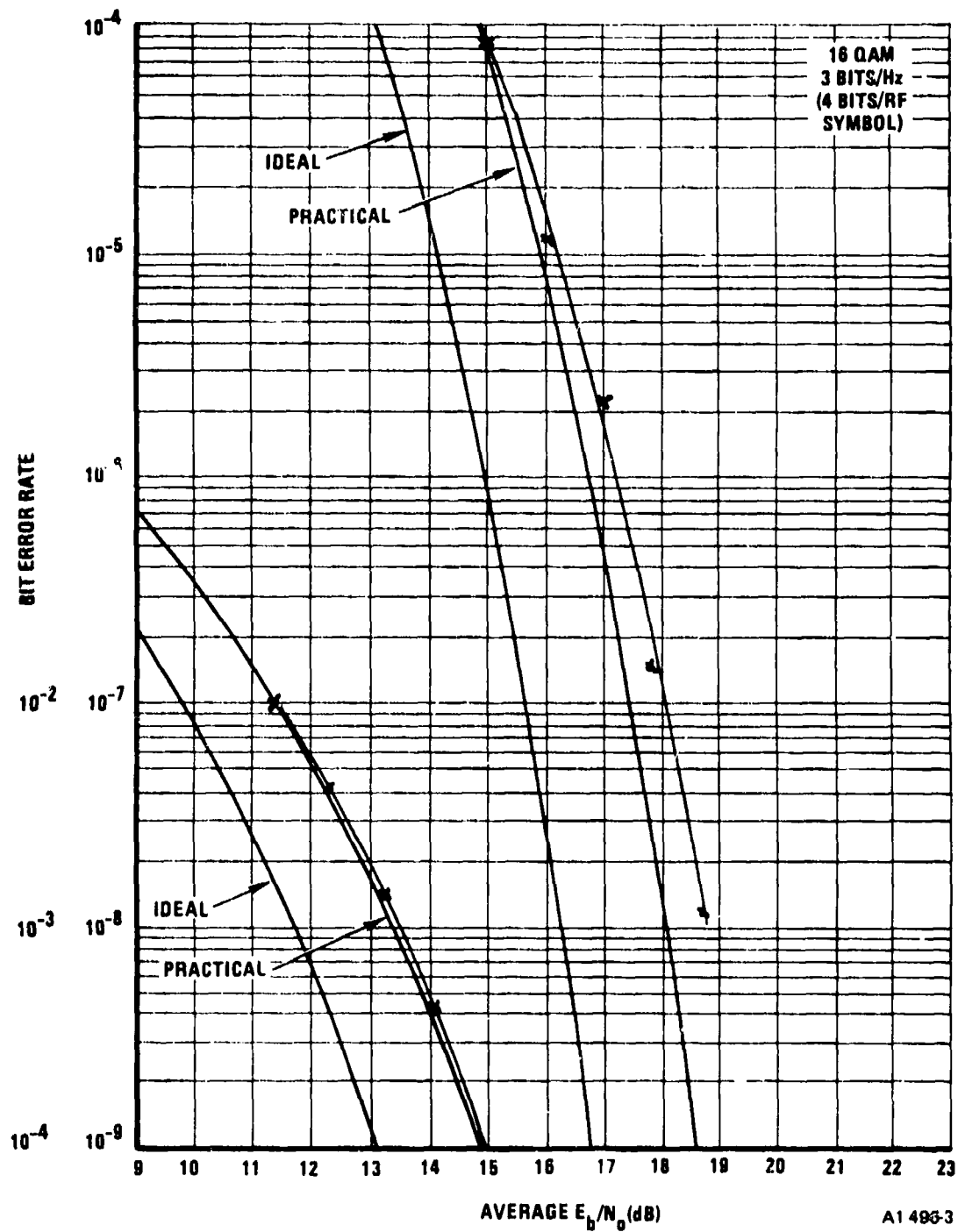


Figure 4.1.3.2-9. 16-QAM Back-to-Back Performance With All Filters

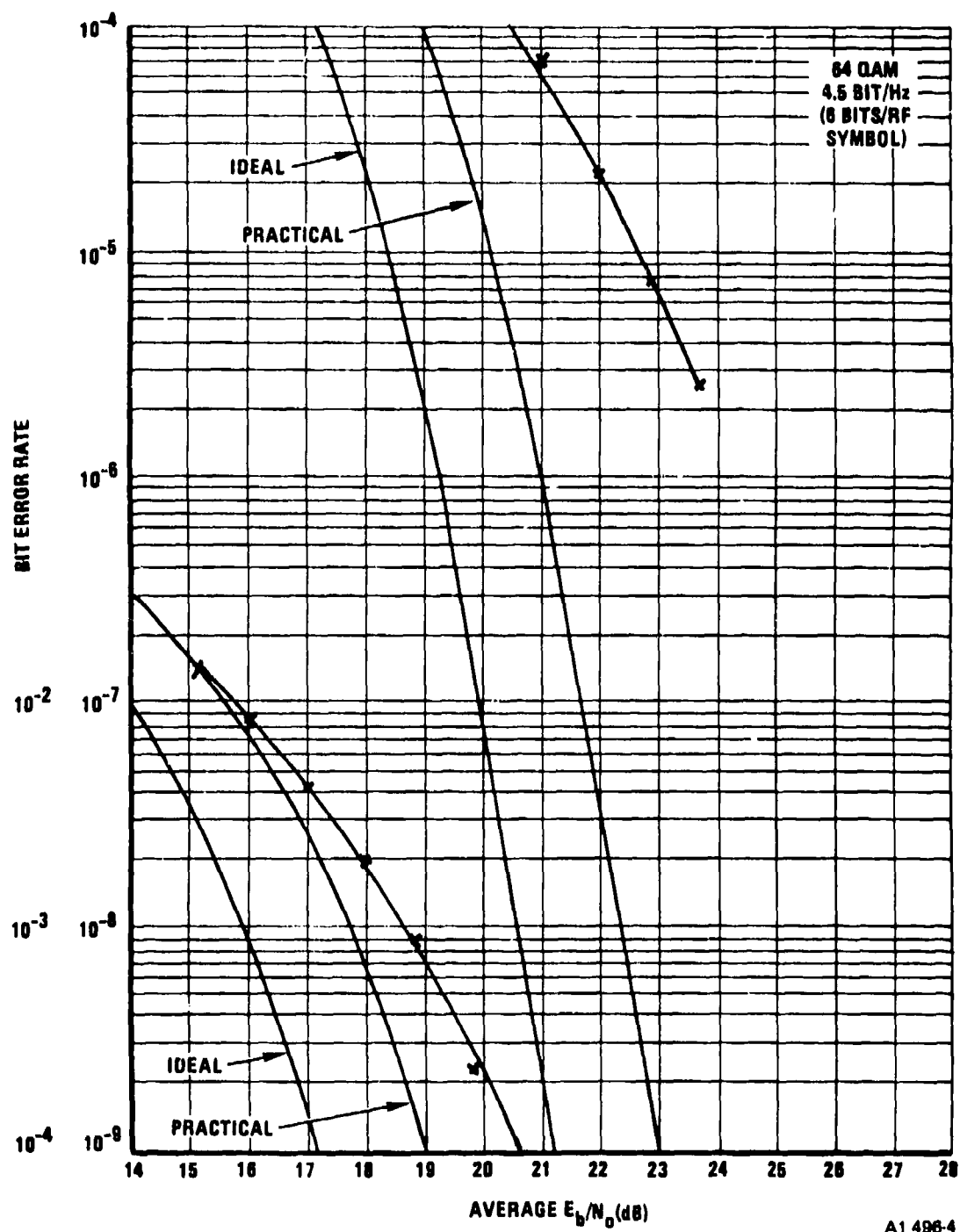


Figure 4.1.3.2-10. 64-QAM Back-to-Back Performance With All Filters

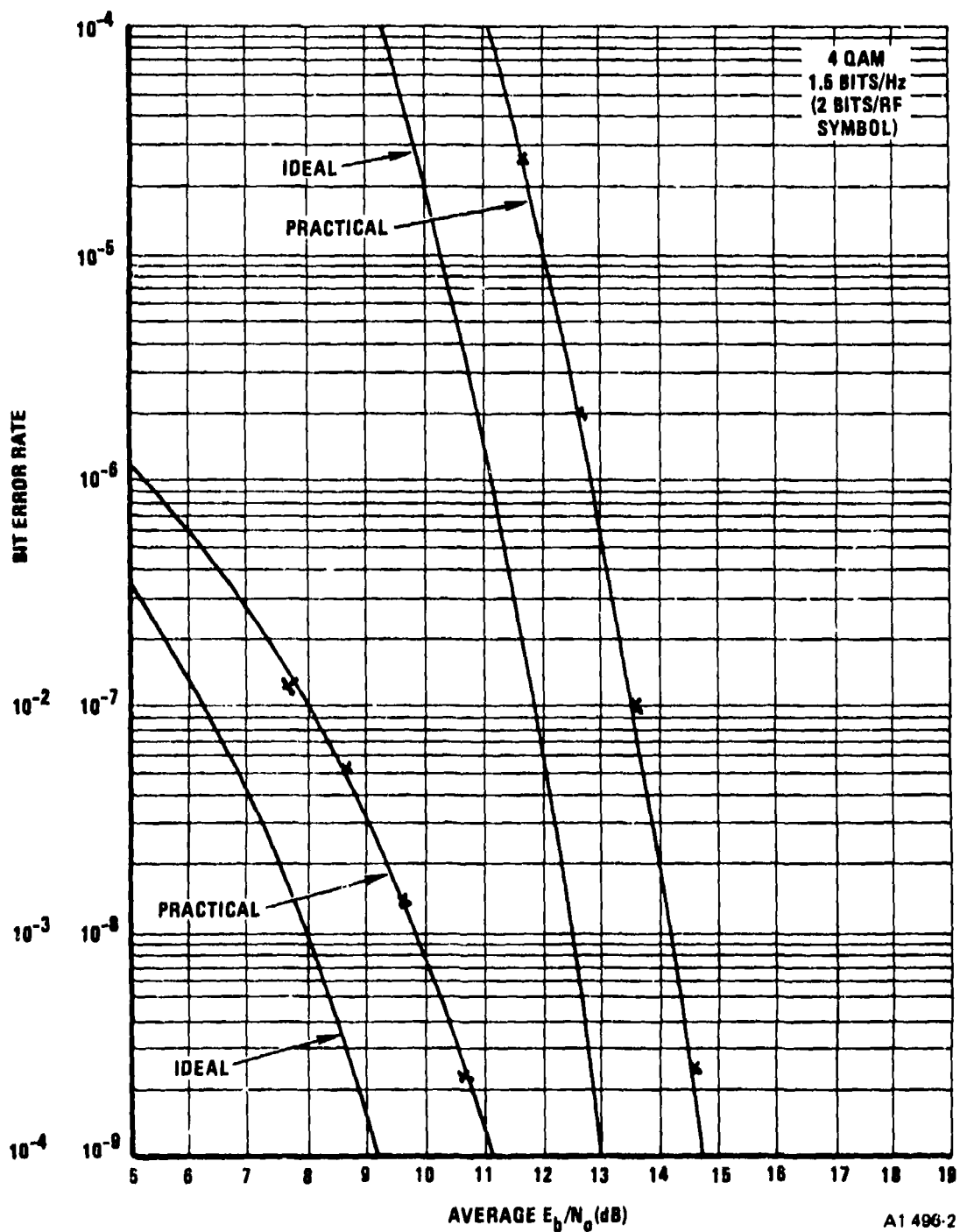


Figure 4.1.3.2-11. 4-QAM Back-to-Back Performance With Optimized Receive Level

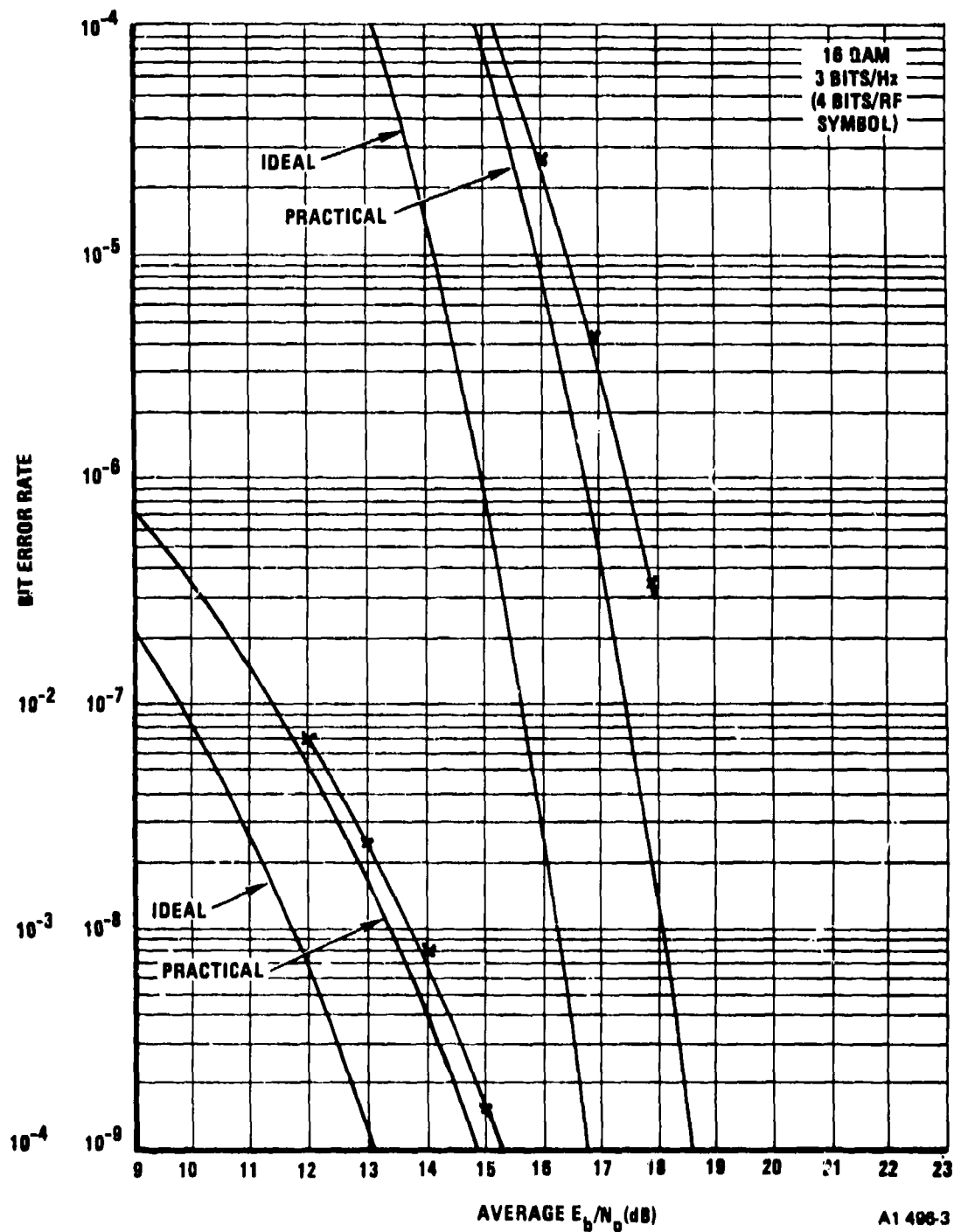


Figure 4.1.3.2-12. 16-QAM Back-to-Back Performance With Optimized Receive Level

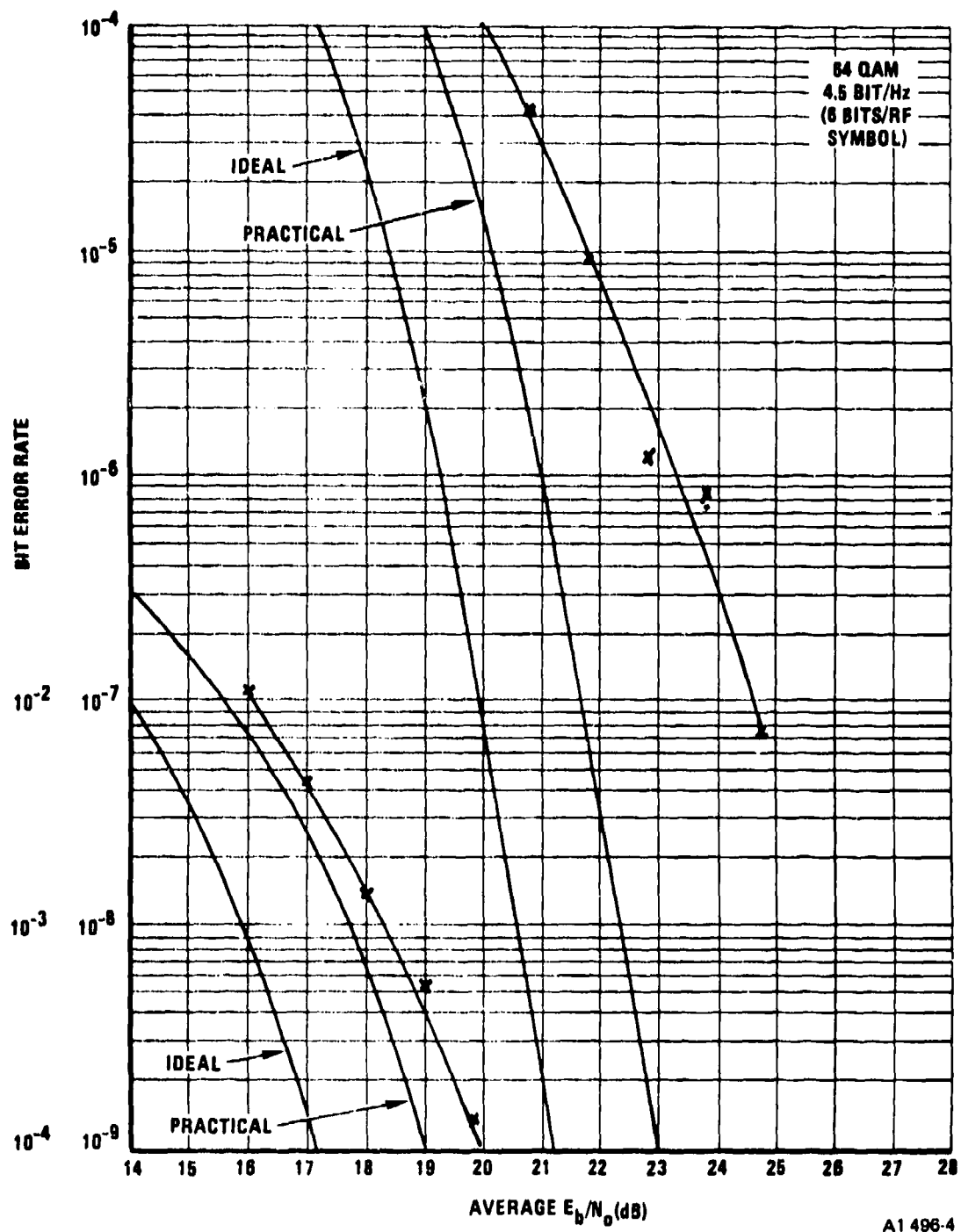


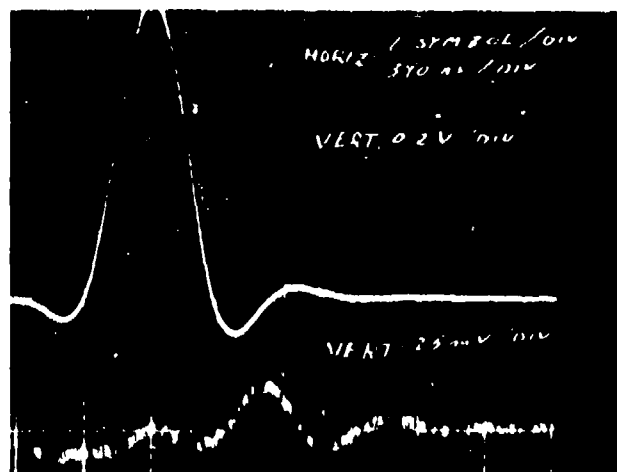
Figure 4.1.3.2-13. 64-QAM Back-to-Back Performance With Optimized Receive Level

The system impulse response and channel crosstalk were measured by passing a single symbol pulse through the system. Figure 4.1.3.2-14(a) shows the impulse response and crosstalk prior to the baseband equalizer and Figure 4.1.3.2-14(b) shows the digitized version of the response prior to the baseband equalizer. Figure 4.1.3.2-15(a) is a repeat of Figure 4.1.3.2-14(b), while Figure 4.1.3.2-15(b) shows the response after the baseband equalizer. Because of the crosstalk caused by imperfect filtering, the system was modified to compensate for crosstalk. First, the outermost taps of the equalizer are zeroed and performance curves run to determine the degradation caused by only using a two-tap equalizer. Figures 4.1.3.2-16 through 4.1.3.2-18 show the results of the experiment.

The baseband equalizer for the I channel is shown in Figure 4.1.3.2-19. The Q channel equalizer is identical to the I channel equalizer. Compensation for Q channel crosstalk into the I channel is accomplished by taking address bits from the Q channel RAM and using them as addresses for the I channel RAM. The configuration shown in Figure 4.1.3.2-20 was used to generate the curves in Figures 4.1.3.2-21 through 4.1.3.2-23. As can be seen, 4-QAM and 16-QAM are within 0.1 dB of the practical curves while 64-QAM is within 1 dB of the practical curves.

All previous data was taken with the predistortion loop disabled since the system was operating in a back-to-back mode. Figures 4.1.3.2-24 through 4.1.3.2-26 were taken with the predistortion loop enabled in the back-to-back mode and show little or no change over the previous performance curves. The same equalizer configuration shown in Figure 4.1.3.2-20 was used for these curves.

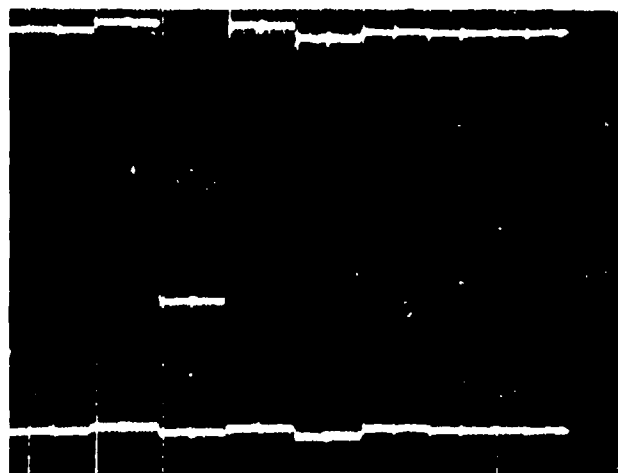
The final set of curves in this section were taken with the test setup shown in Figure 4.1.3.2-27, and with the TWT 1 dB from saturation. When operated through the link simulator and TWT's, the impulse response changed slightly which required the I channel  $i+2$  one-bit tap to be disconnected from the RAM and the I channel  $i-2$  one-bit tap to be connected to the RAM. The performance for these conditions is shown in Figures 4.1.3.2-28 through 4.1.3.2-30.



(a)

**FILTER IMPULSE  
RESPONSE**

**INPUT: 1 SYMBOL PERIOD  
WIDE P.S. IMPULSE  
ON I CHANNEL  
OUTPUT: TOP TRACE  
I CHANNEL  
BOTTOM TRACE AND  
CHANNEL  
FS = 1 Vp-p**



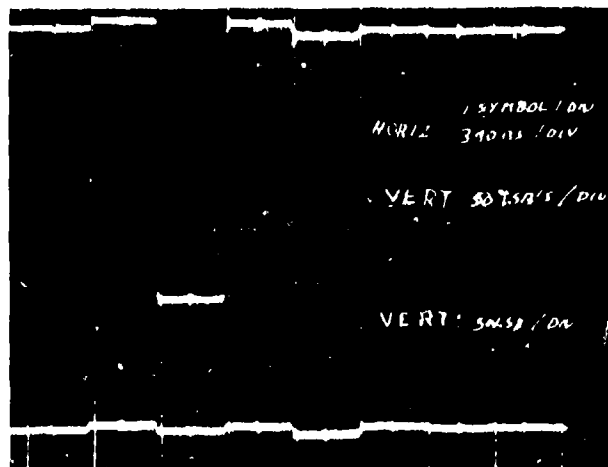
(b)

**DIGITIZED  
VERSION OF  
ABOVE TRACE**

A1496-7

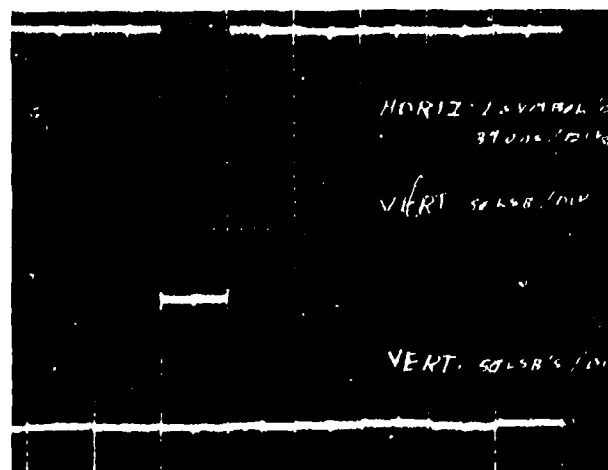
Figure 4.1.3.2-14. System Impulse Response





(a)

UNEQUALIZED  
IMPULSE RESPONSE  
ON I AND Q CHANNEL



(b)

EQUALIZED  
RESPONSE  
ON I AND Q CHANNEL

A1496-8

Figure 4.1.3.2-15. System Impulse Response Before and After the Baseband Equalizer

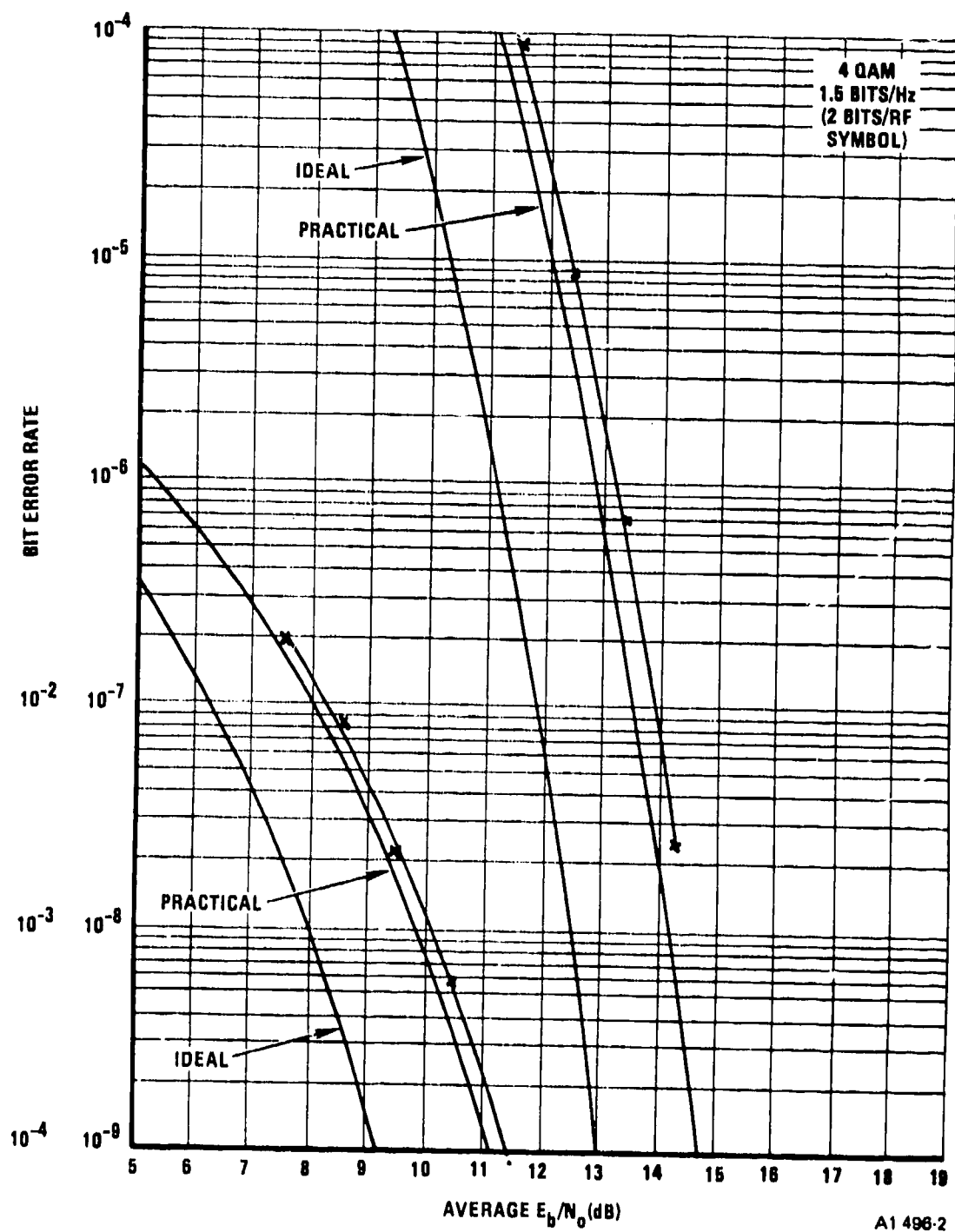


Figure 4.1.3.2-16. 4-QAM Back-to-Back Performance With Two-Tap Equalizer

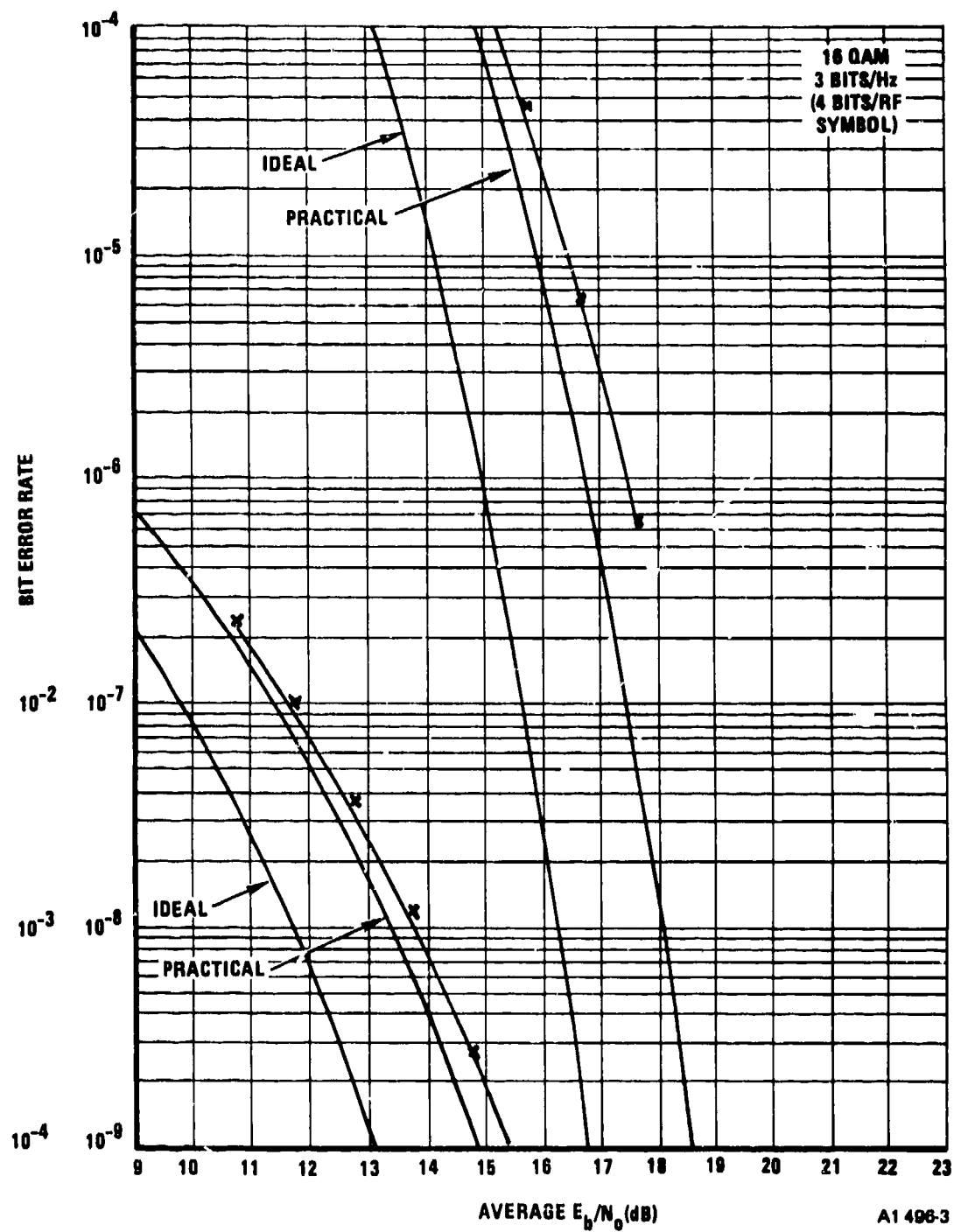


Figure 4.1.3.2-17. 16-QAM Back-to-Back Performance With Two-Tap Equalizer

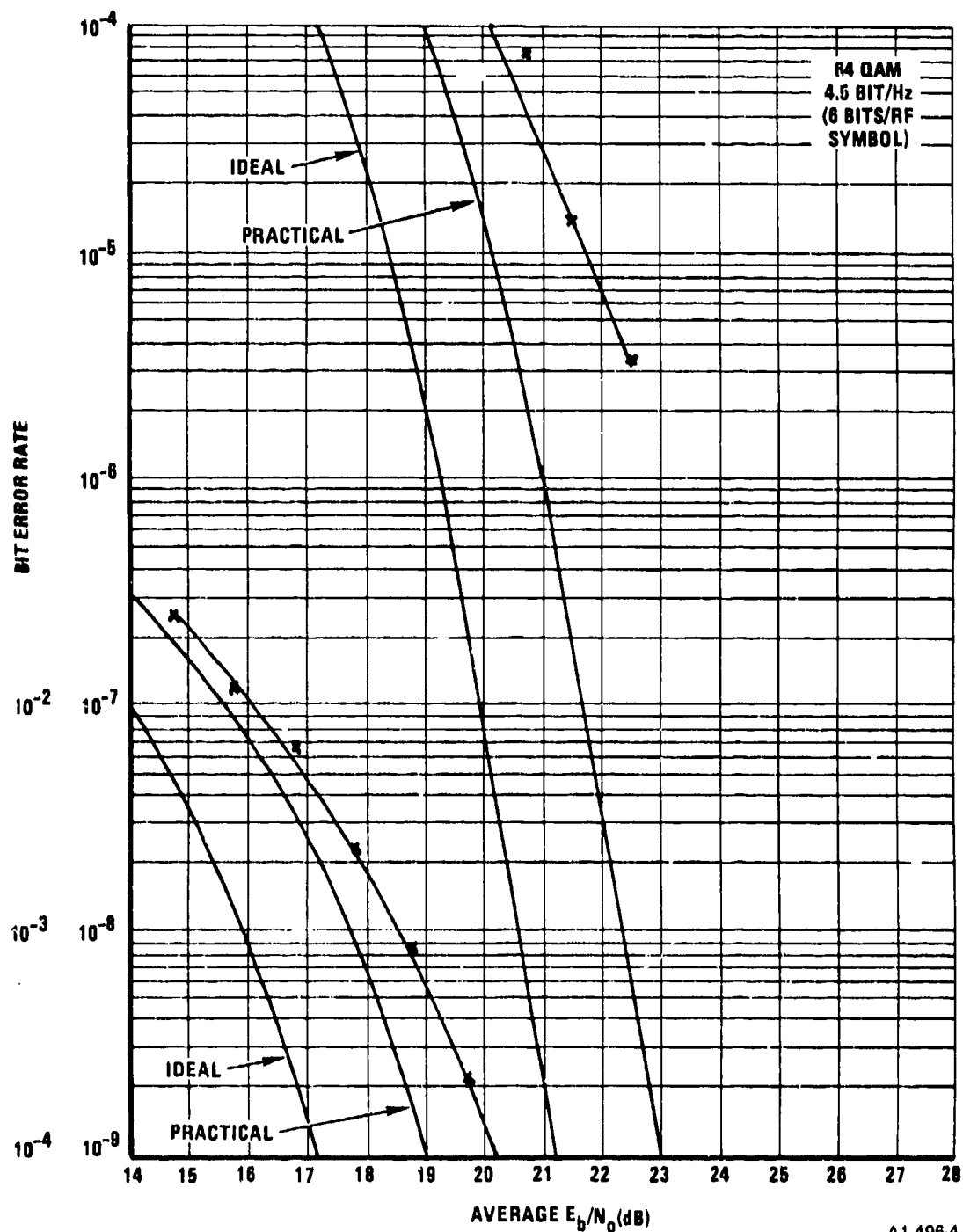
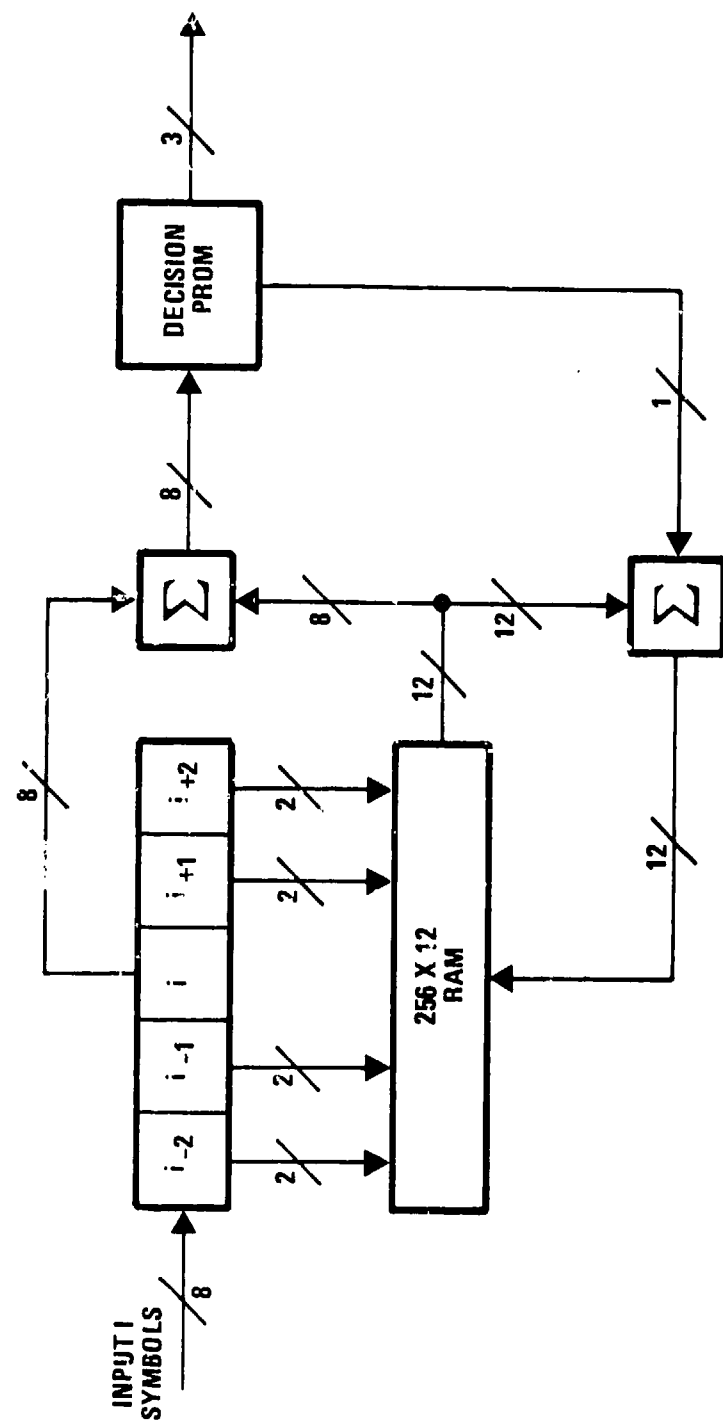
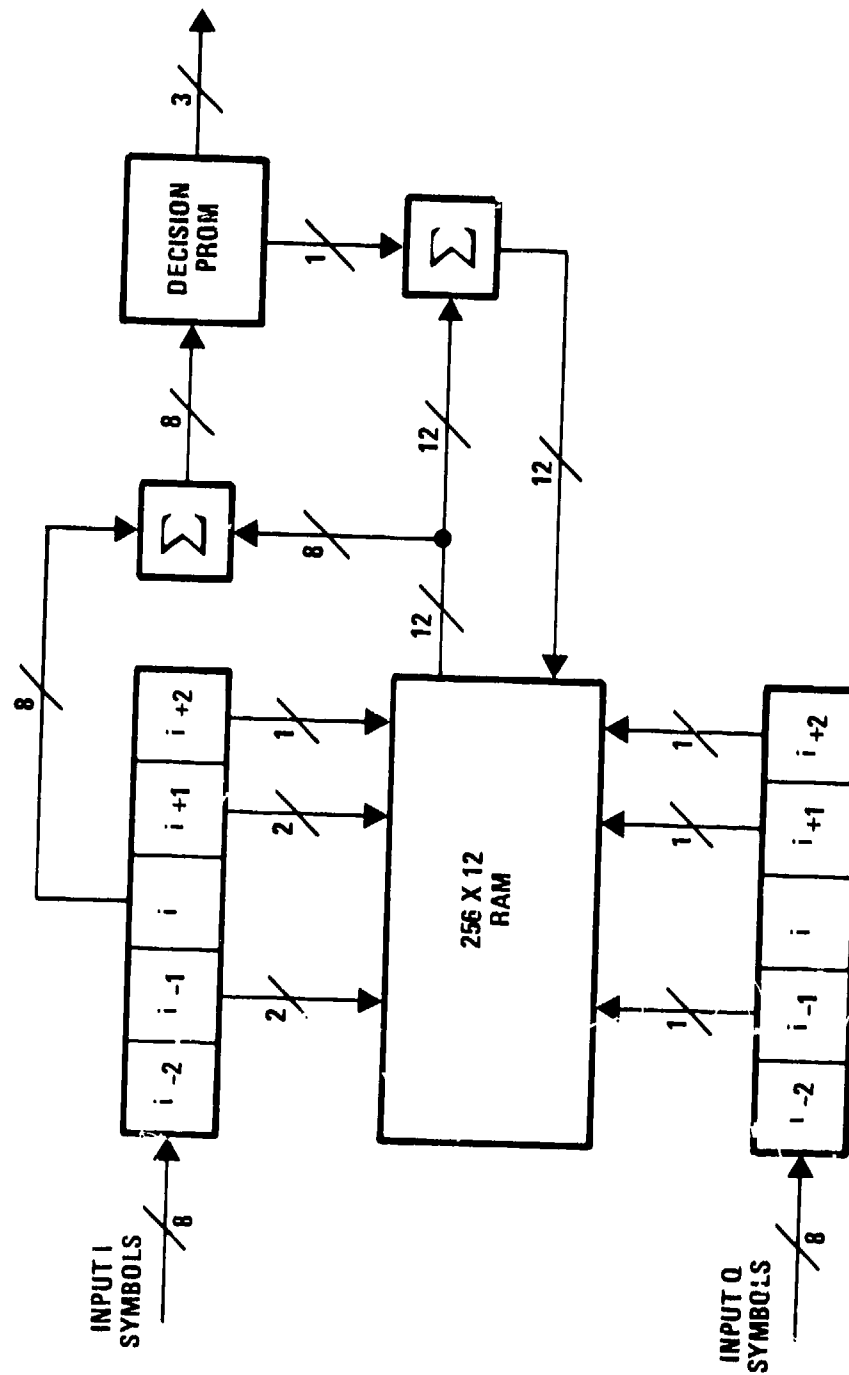


Figure 4.1.3.2-18. 64-QAM Back-to-Back Performance With Two-Tap Equalizer



A1496-25

Figure 4.1.3.2-19. 1 Channel Equalizer Configured for Intersymbol Interference Only



A1496-26

Figure 4.1.3.2-20. I Channel Equalizer Configured for Q Channel Crosstalk Compensation

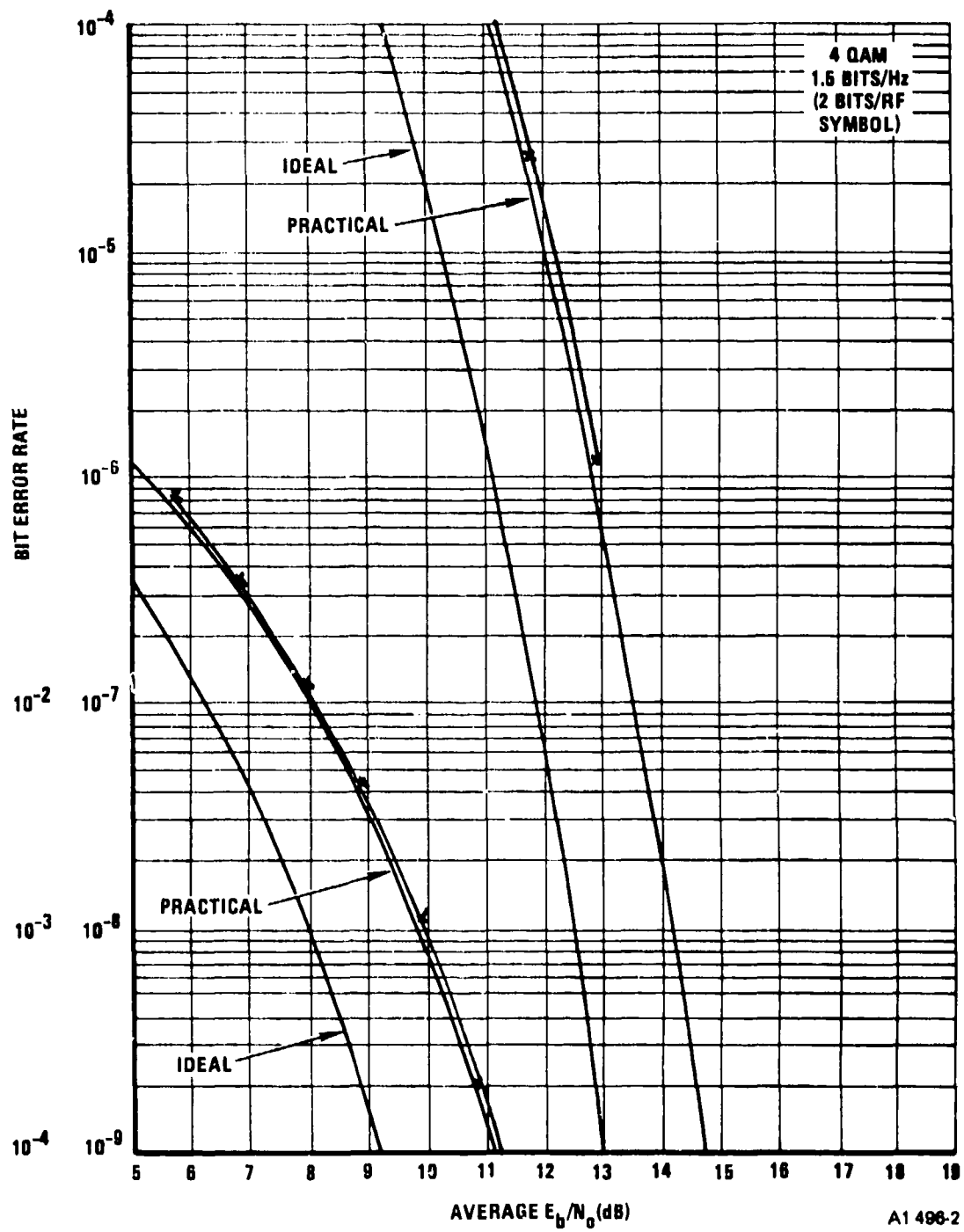


Figure 4.1.3.2-21. 4-QAM Back-to-Back Performance With Crosstalk Compensation

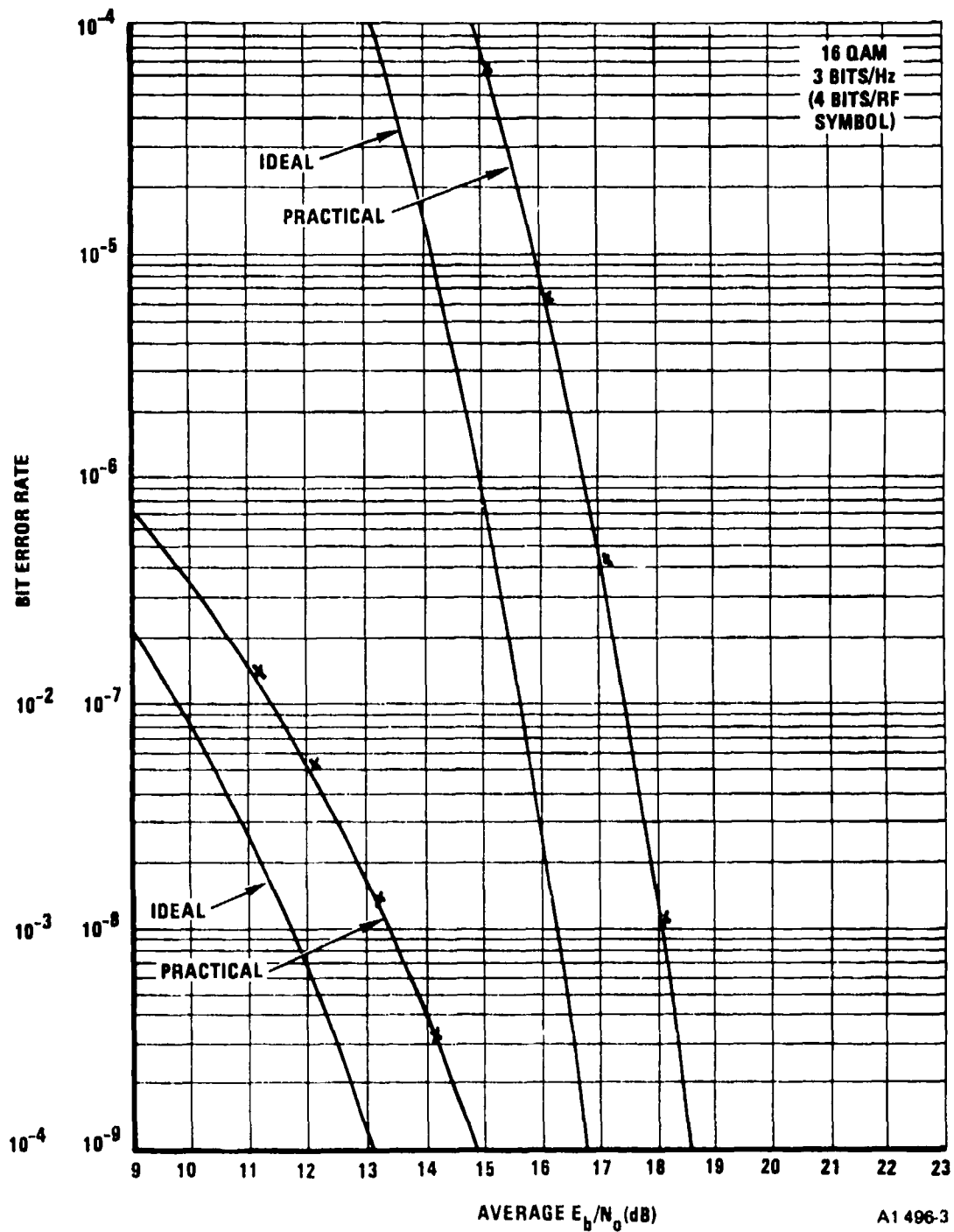


Figure 4.1.3.2-22. 16-QAM Back-to-Back Performance With Crosstalk Compensation



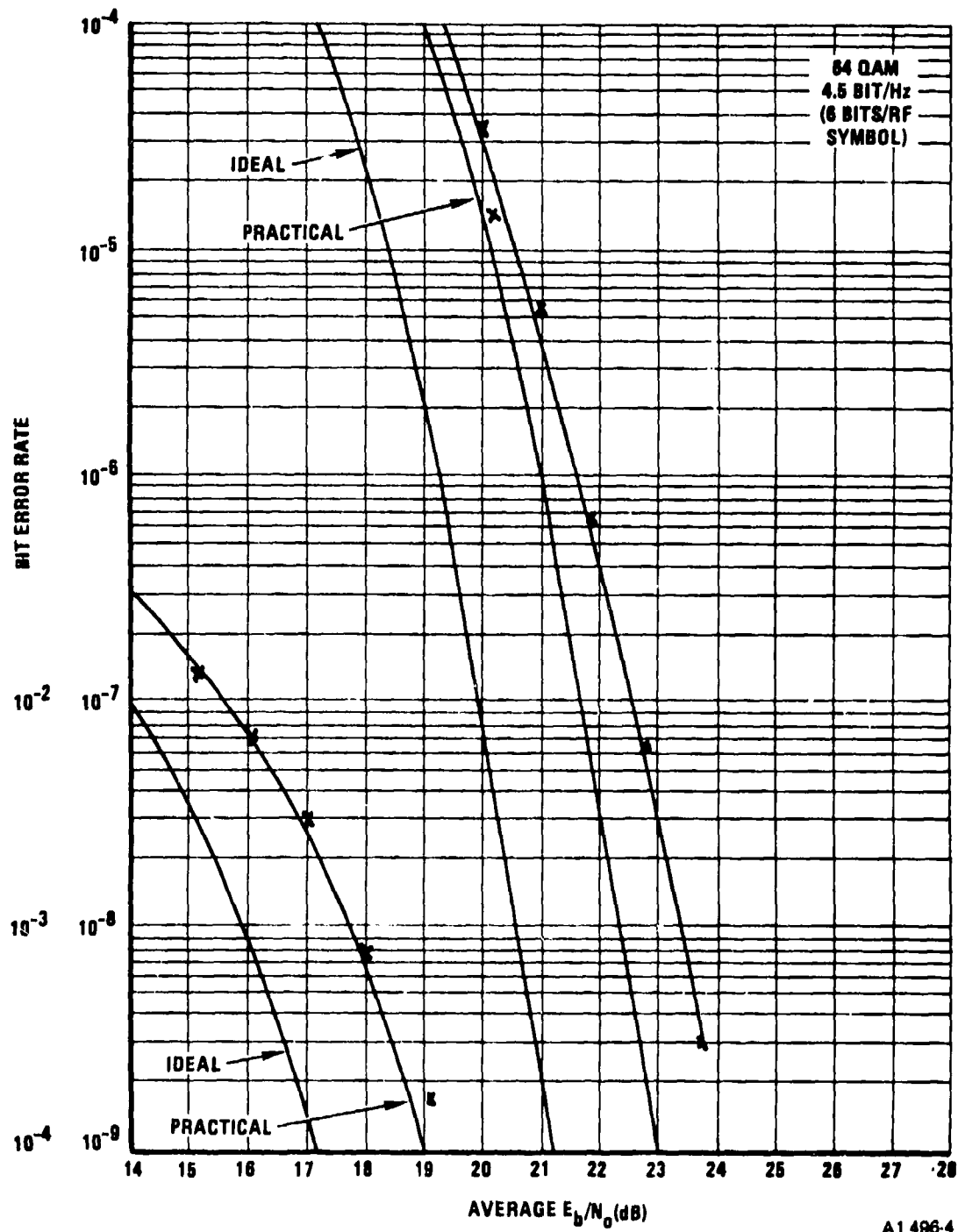


Figure 4.1.3.2-23. 64-QAM Back-to-Back Performance With Crosstalk Compensation

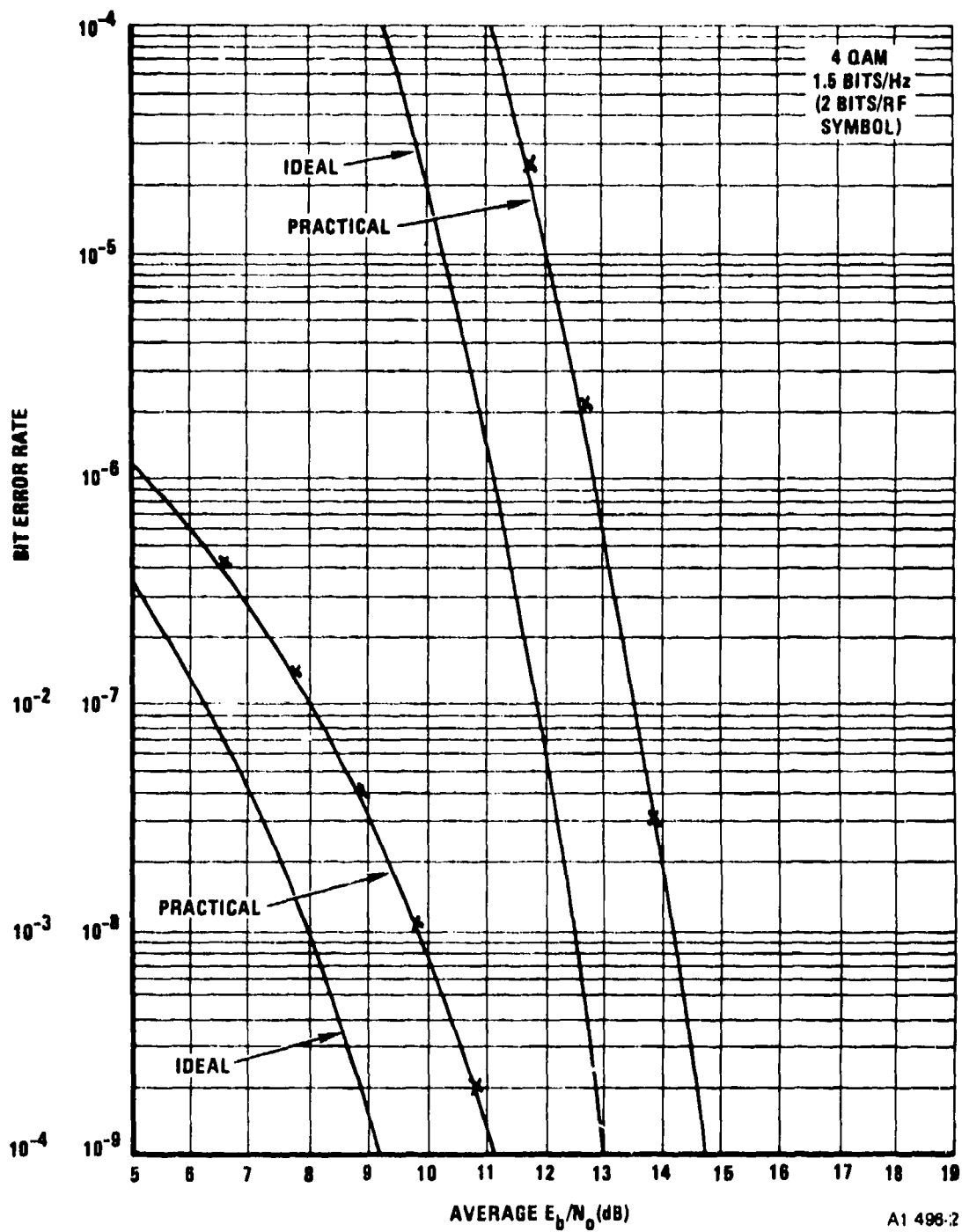


Figure 4.1.3.2-24. 4-QAM Back-to-Back Performance With Predistortion Enabled

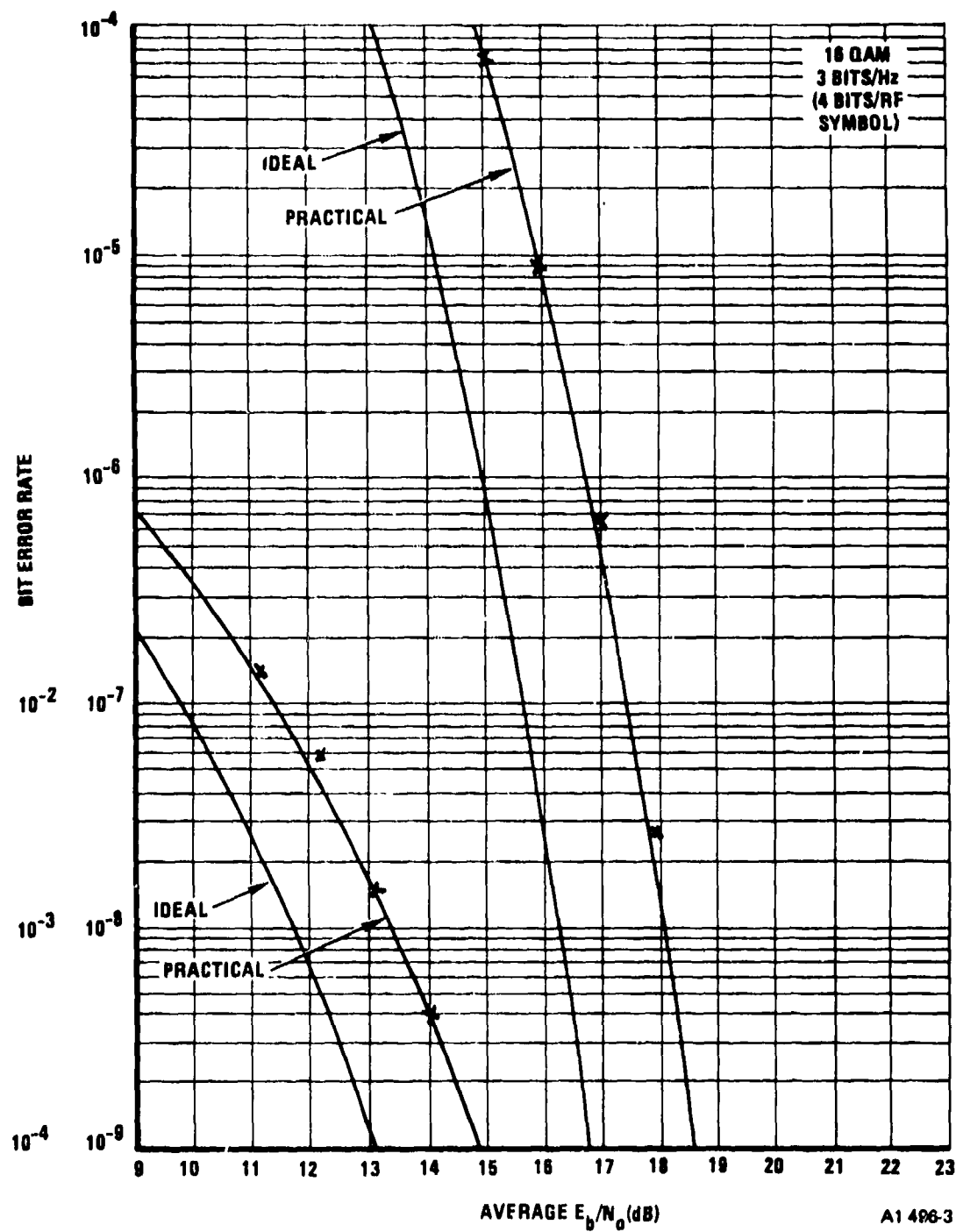


Figure 4.1.3.2-25. 16-QAM Back-to-Back Performance With Predistortion Enabled

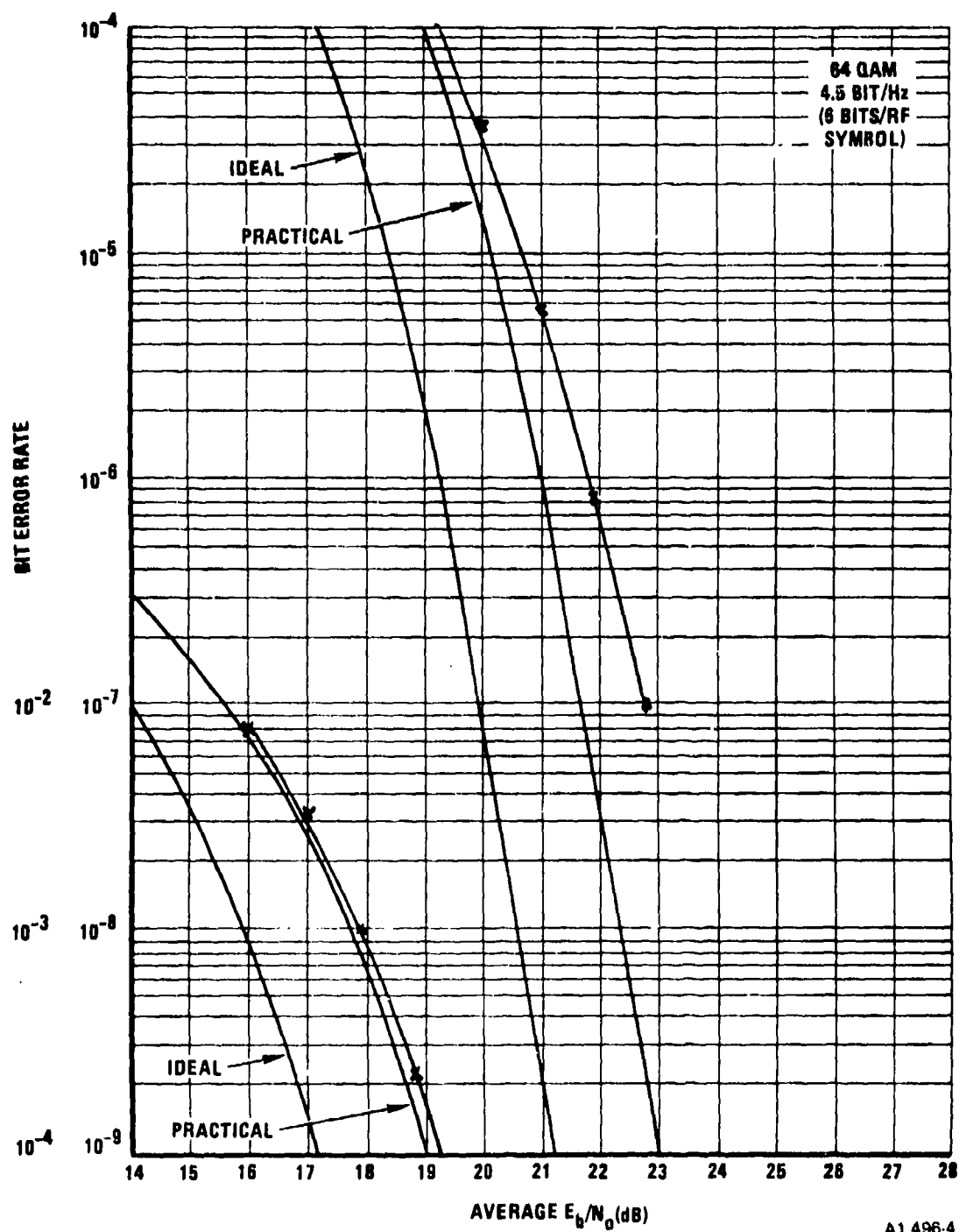
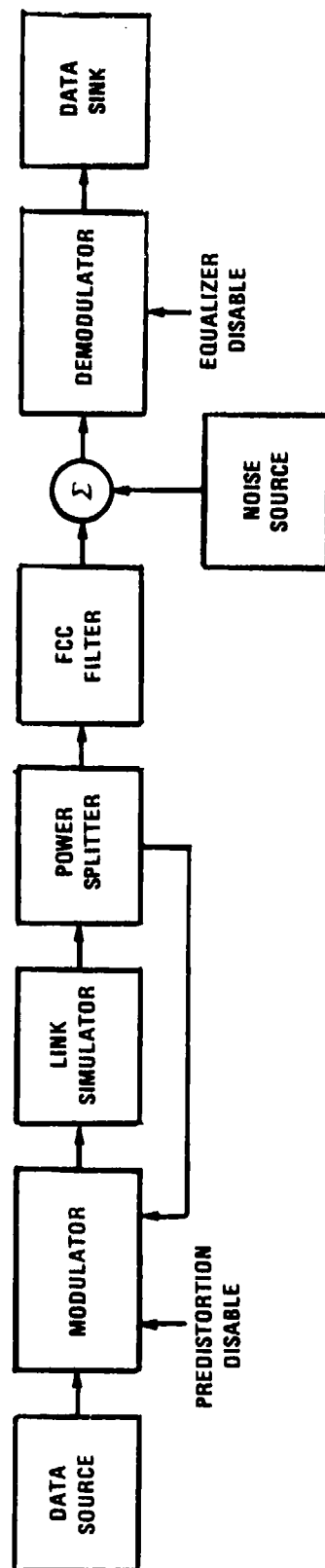


Figure 4.1.3.2-26. 64-QAM Back-to-Back Performance With Predistortion Enabled



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Figure 4.1.3.2-27. Simulated Link Test

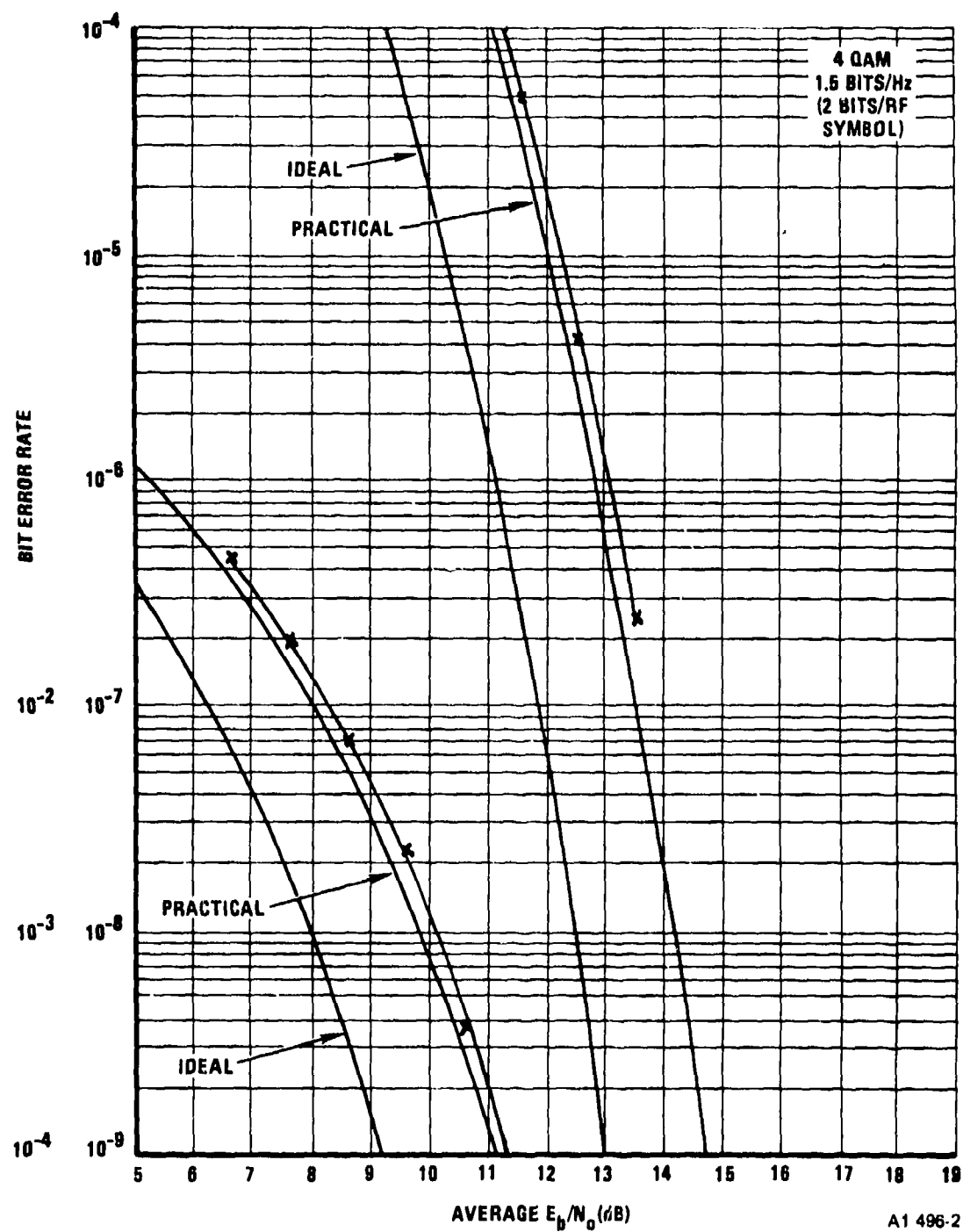


Figure 4.1.3.2-28. 4-QAM Link Performance With Modified Baseband Equalizer

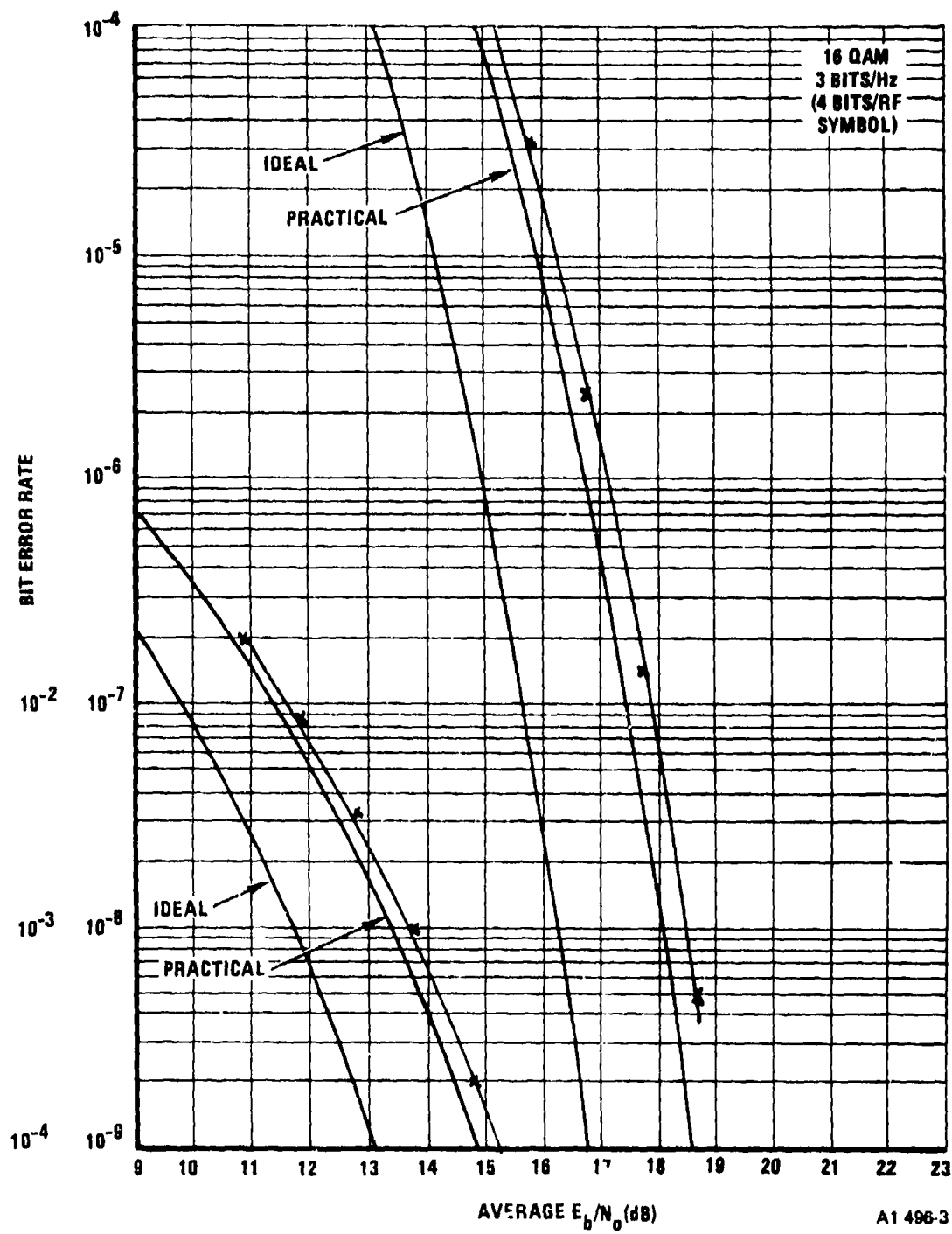


Figure 4.1.3.2-29. 16-QAM Link Performance With Modified Baseband Equalizer

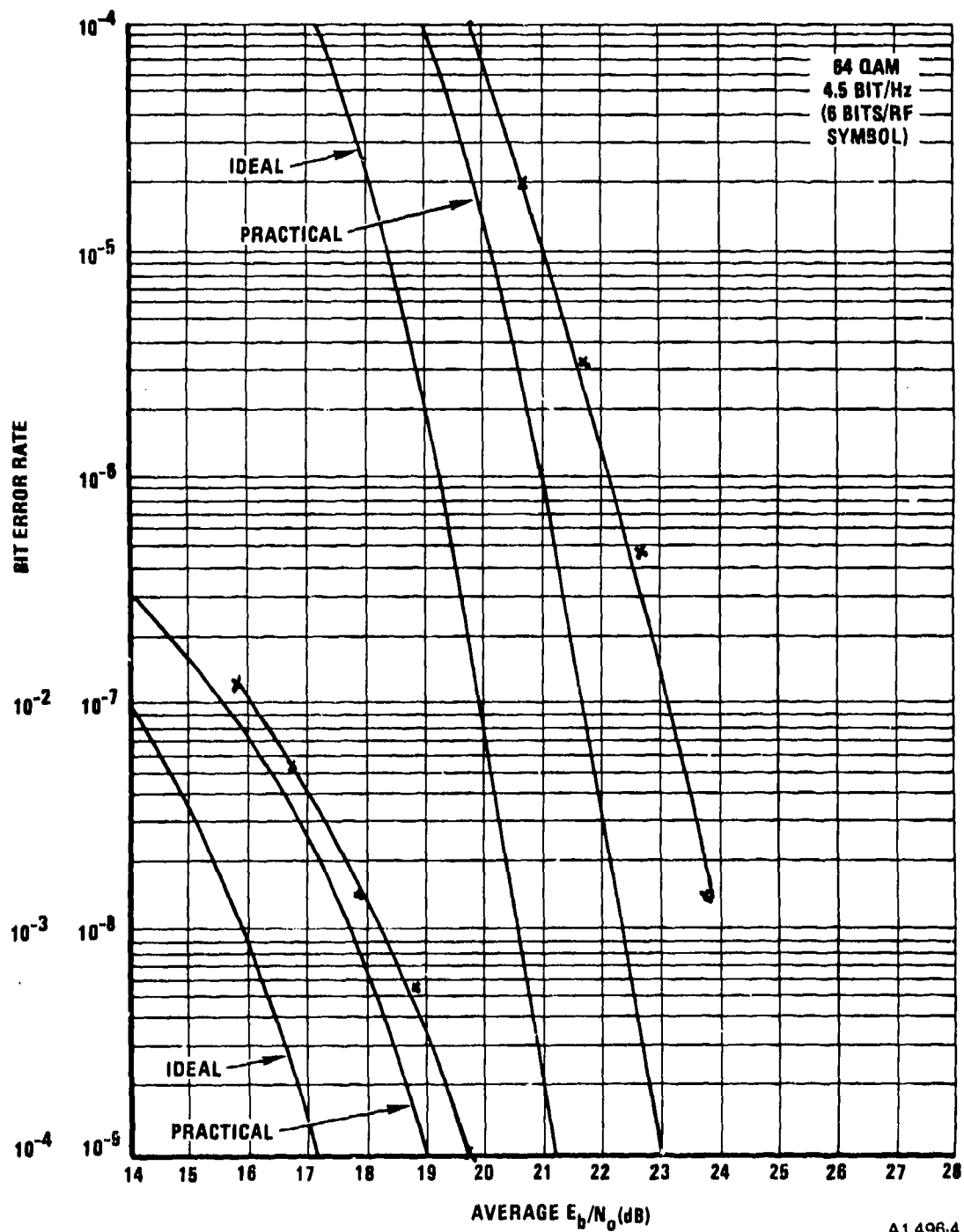


Figure 4.1.3.2-30. 64-QAM Link Performance With Modified Baseband Equalizer



#### 4.1.3.3 In-Plant Test Results

The performance curves in this section were accomplished using the test plan found in Appendix A. The mask filter was the final version that did meet FCC requirements (see Paragraph 4.1.1 for results). Since this filter was more narrow and had more severe group delay distortion, the analog equalizer required redesign. The resultant receive filter/equalizer response shown in Figure 4.1.3.3-1 had a measured noise bandwidth of 8.06 MHz, which is a 2 dB degradation from the previous receive filter/equalizer combination whose noise bandwidth was 5 MHz. The composite mask filter, receive filter, and equalizer response is shown in Figure 4.1.3.3-2 along with the LMT simulation filter responses.

The first set of data was taken in a back-to-back mode at 70 MHz and is shown in Figures 4.1.3.3-3 through 4.1.3.3-5. When the 2 dB increase in receive filter noise bandwidth is taken into account, the performance is essentially the same as previously (Figures 4.1.3.2-24 through 4.1.3.2-26). Disabling the digital baseband equalizer costs about 0.1 to 0.2 dB in 4-QAM, 0.2 to 0.4 dB in 16-QAM, and 2 to 4 dB in 64-QAM. As expected, disabling the adaptive predistortion had no effect in the back-to-back mode.

The next set of data (Figures 4.1.3.3-6 through 4.1.3.3-8) was taken with the TWT backed down 15 dB from saturation. In 4-QAM, there was little or no difference in performance with predistortion enabled or disabled, but a 0.2 to 0.4 dB degradation when the adaptive baseband equalizer was disabled. For 16-QAM, there was less than 0.1 dB variation for adaptive predistortion, but a 0.5 to 1 dB degradation when the baseband equalizer was disabled. In the 64-QAM case, there was slight ( 0.1 dB) variation for predistortion, but 1.5 to 4 dB for disabling the baseband equalizer.

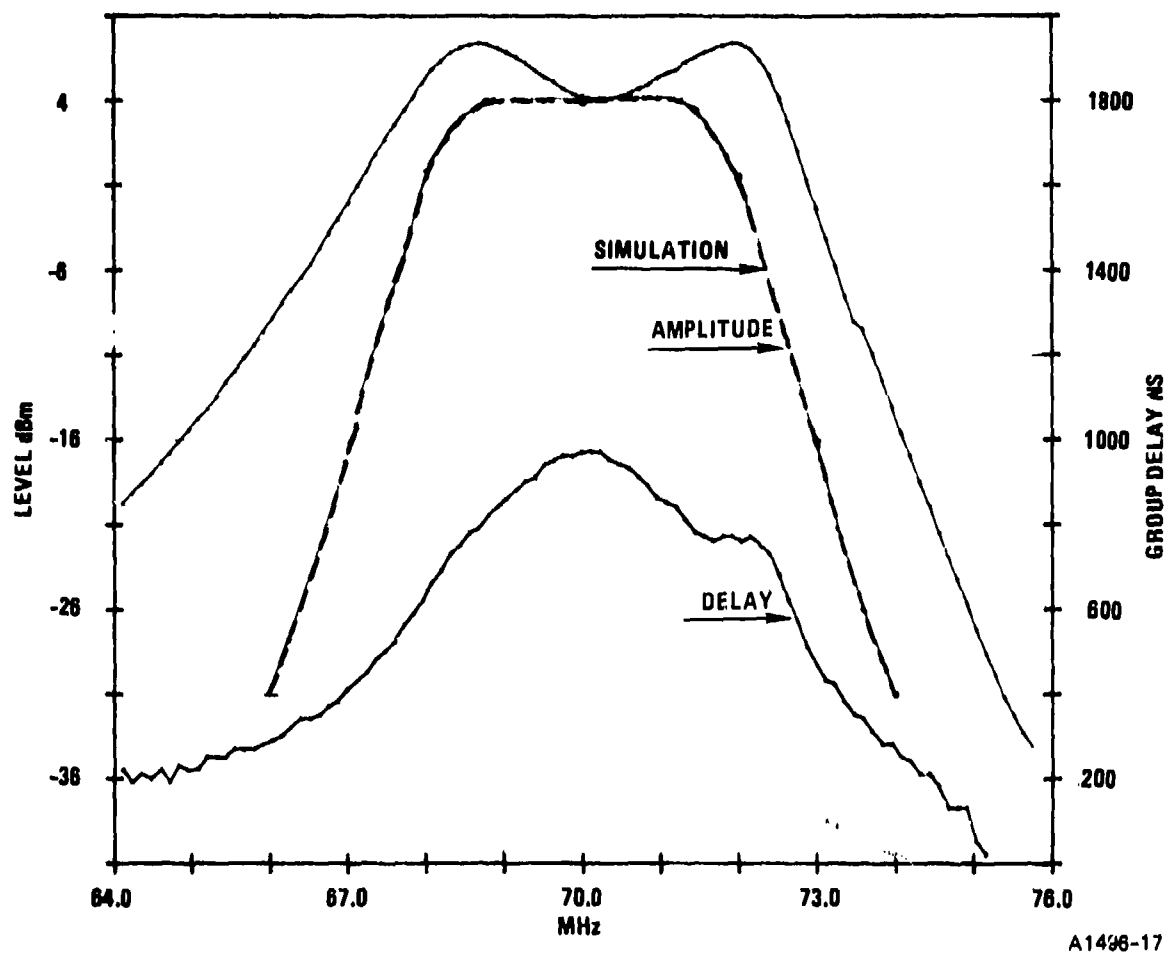


Figure 4.1.3.3-1. Modified Receive Filter and Equalizer

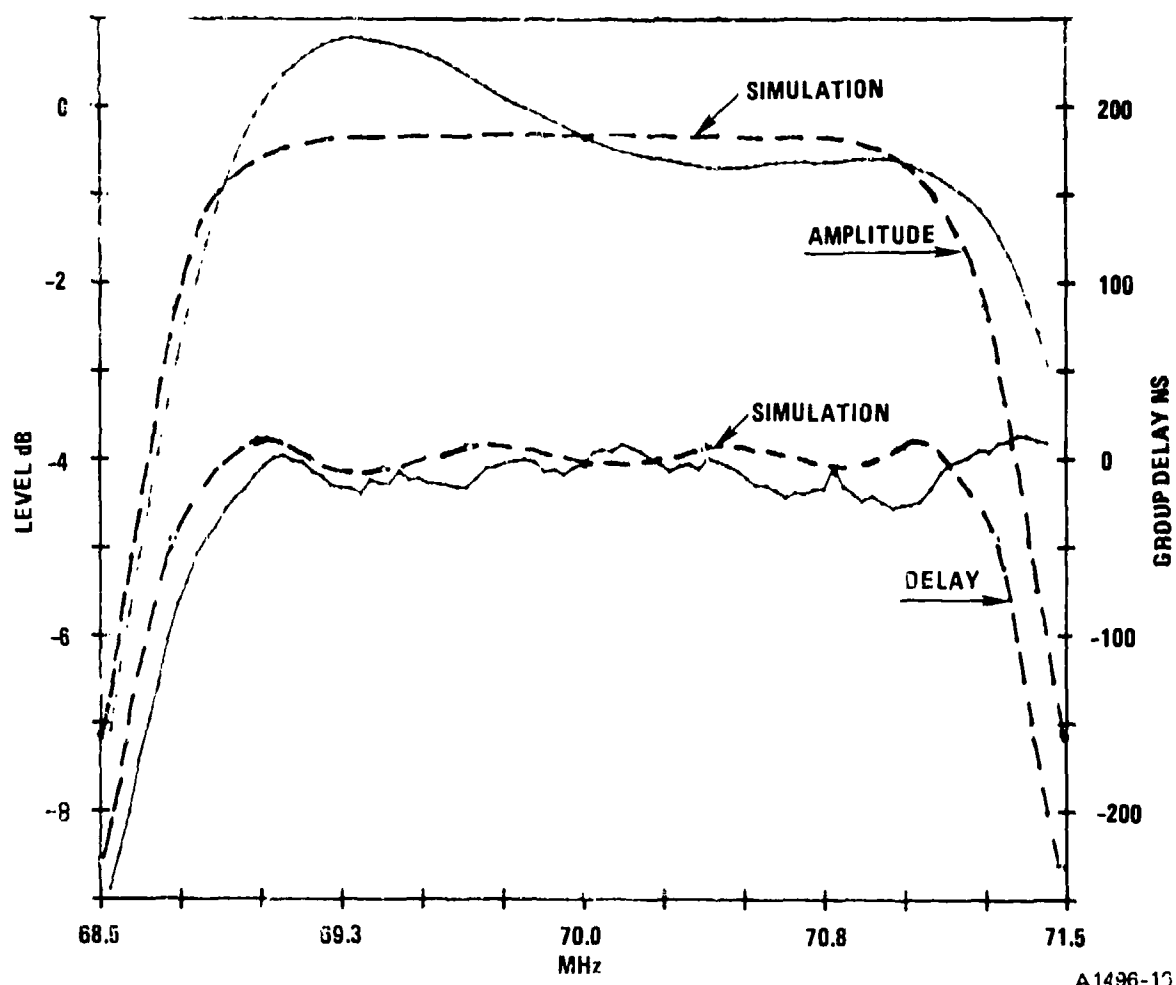


Figure 4.1.3.3-2. Composite Filter Response

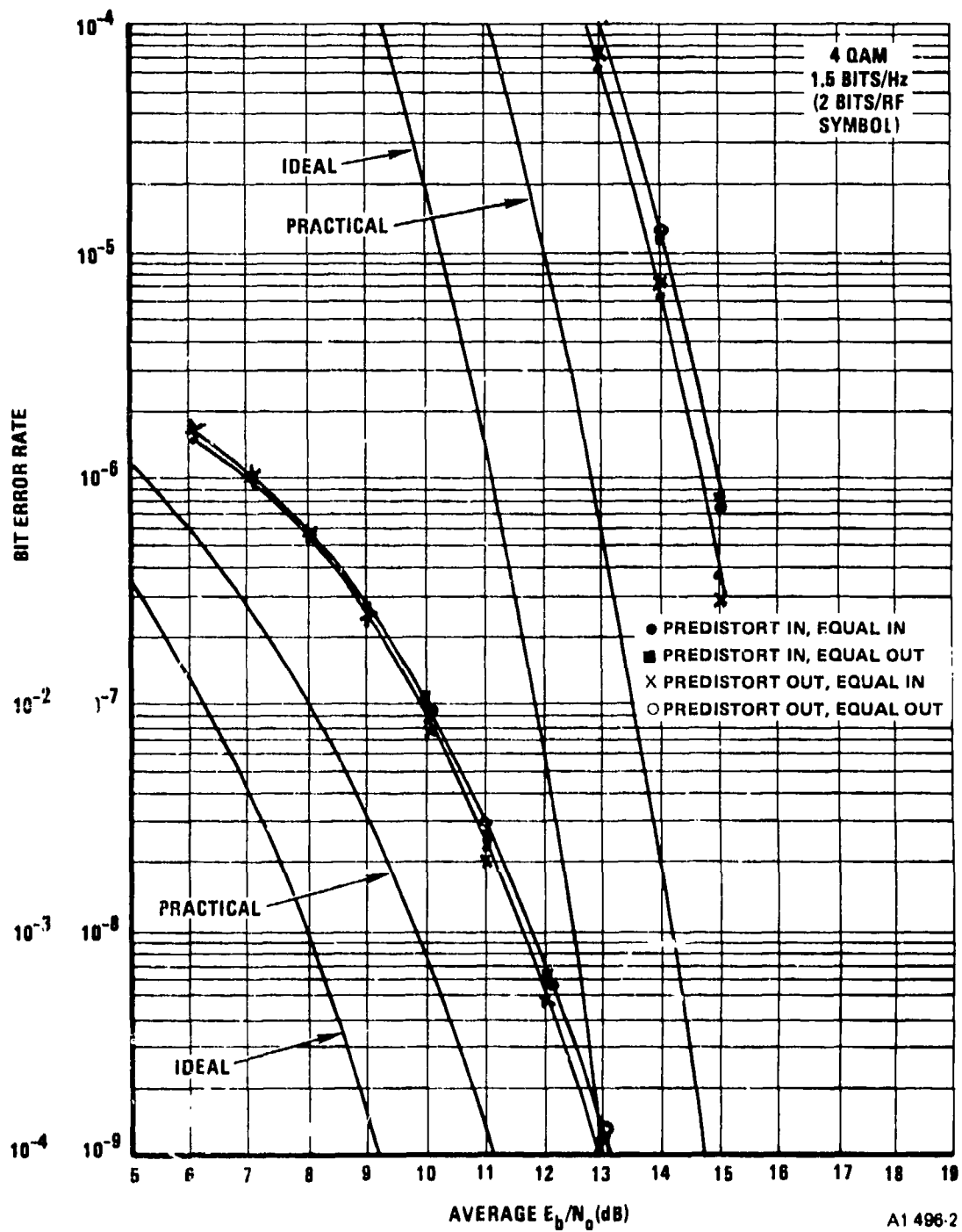


Figure 4.1.3.3-3. 4-QAM Back-to-Back With and Without Predistortion and Equalizer

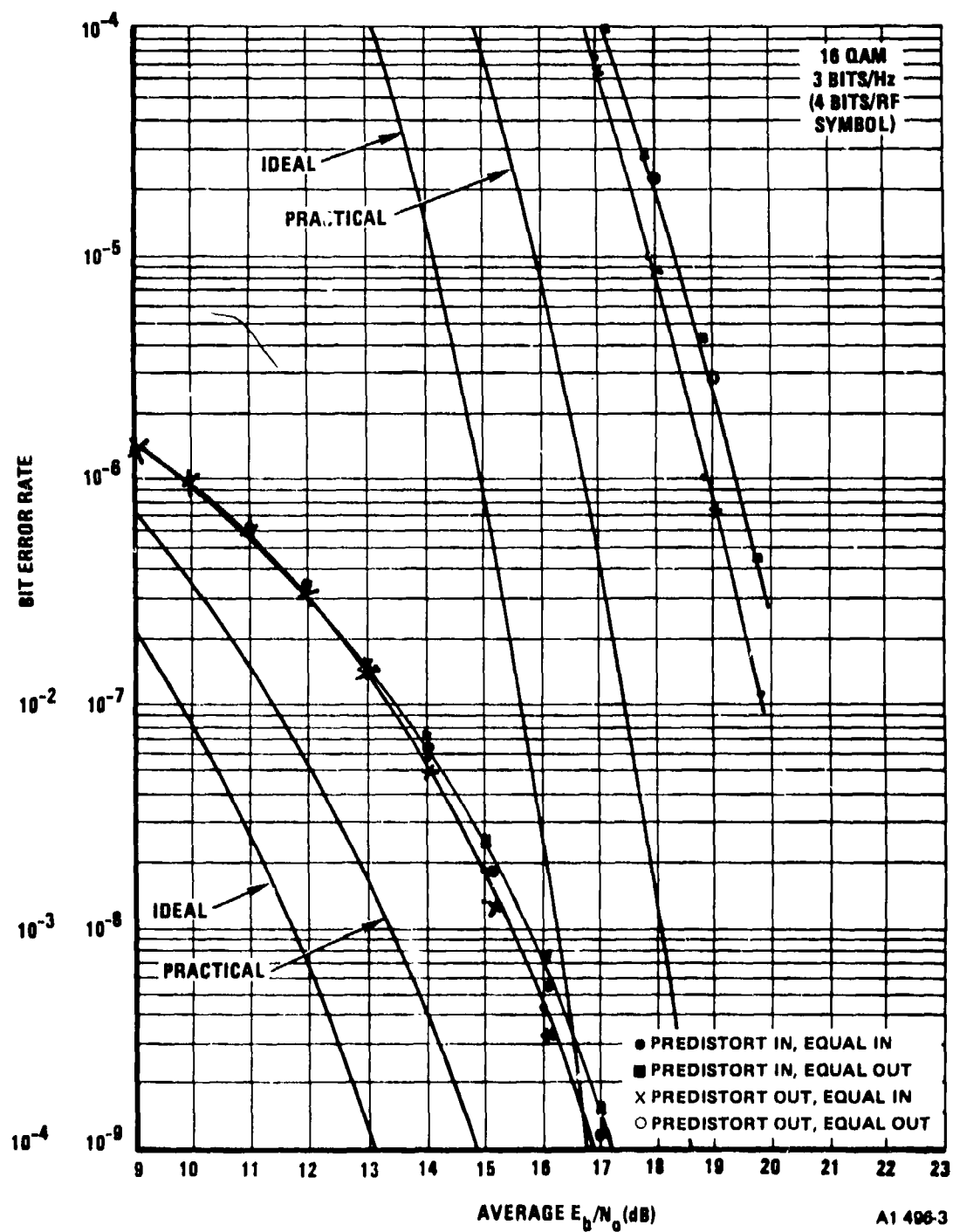


Figure 4.1.3.3-4. 16-QAM Back-to-Back With and Without Predistortion and Equalizer

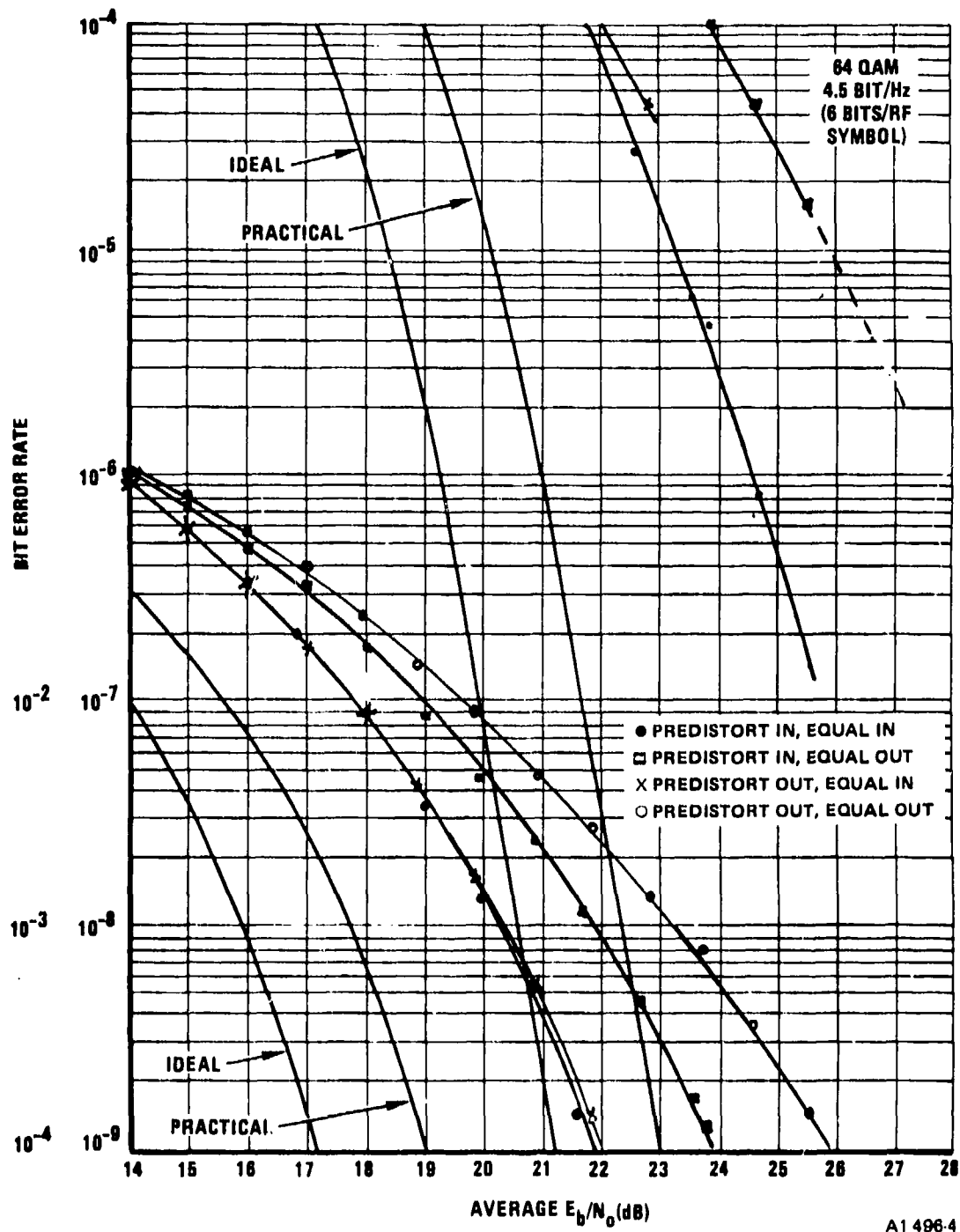


Figure 4.1.3.3-5. 64-QAM Back-to-Back With and Without Predistortion and Equalizer

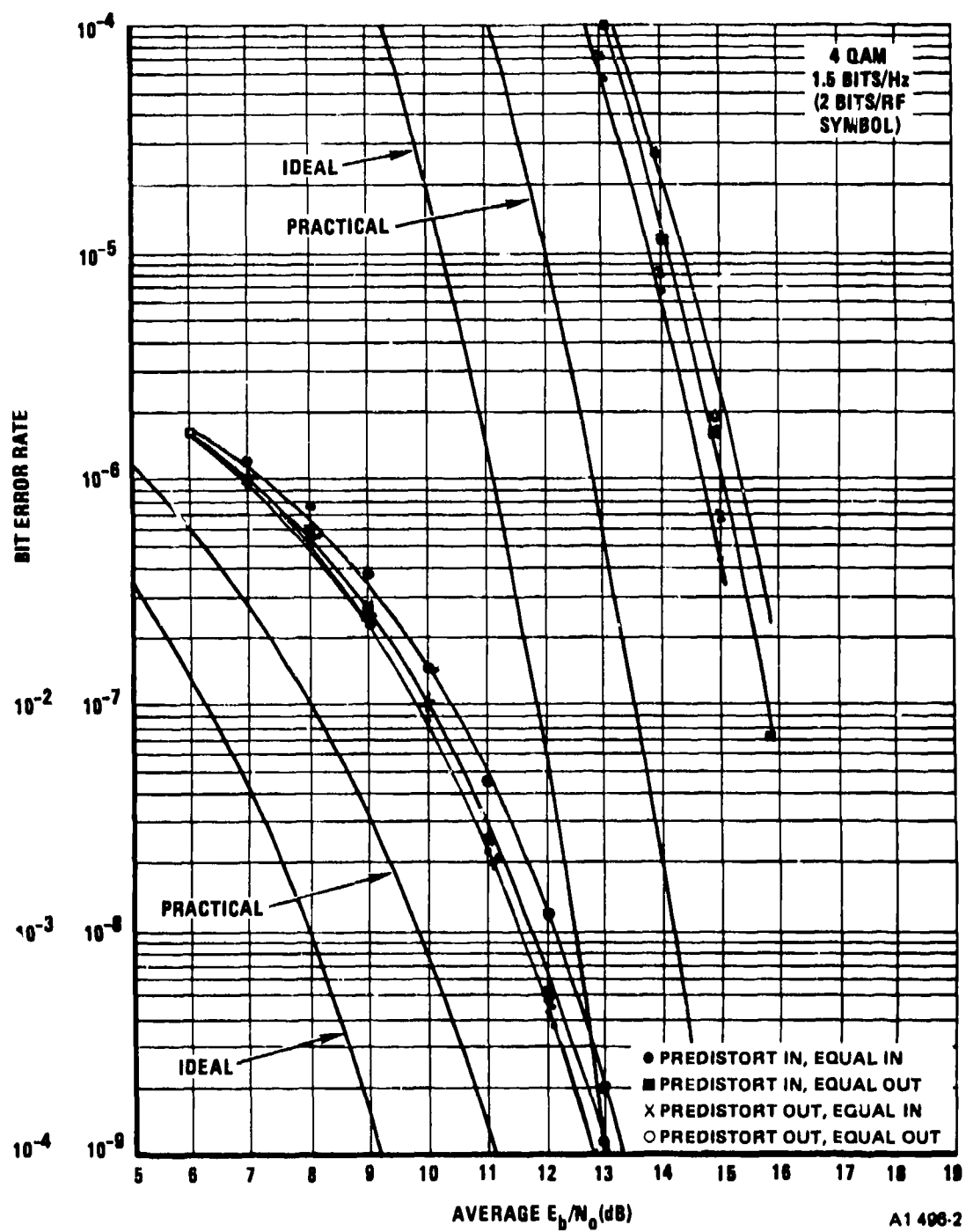


Figure 4.1.3.3-6. 4-QAM Performance With TWT 15 dB from Saturation

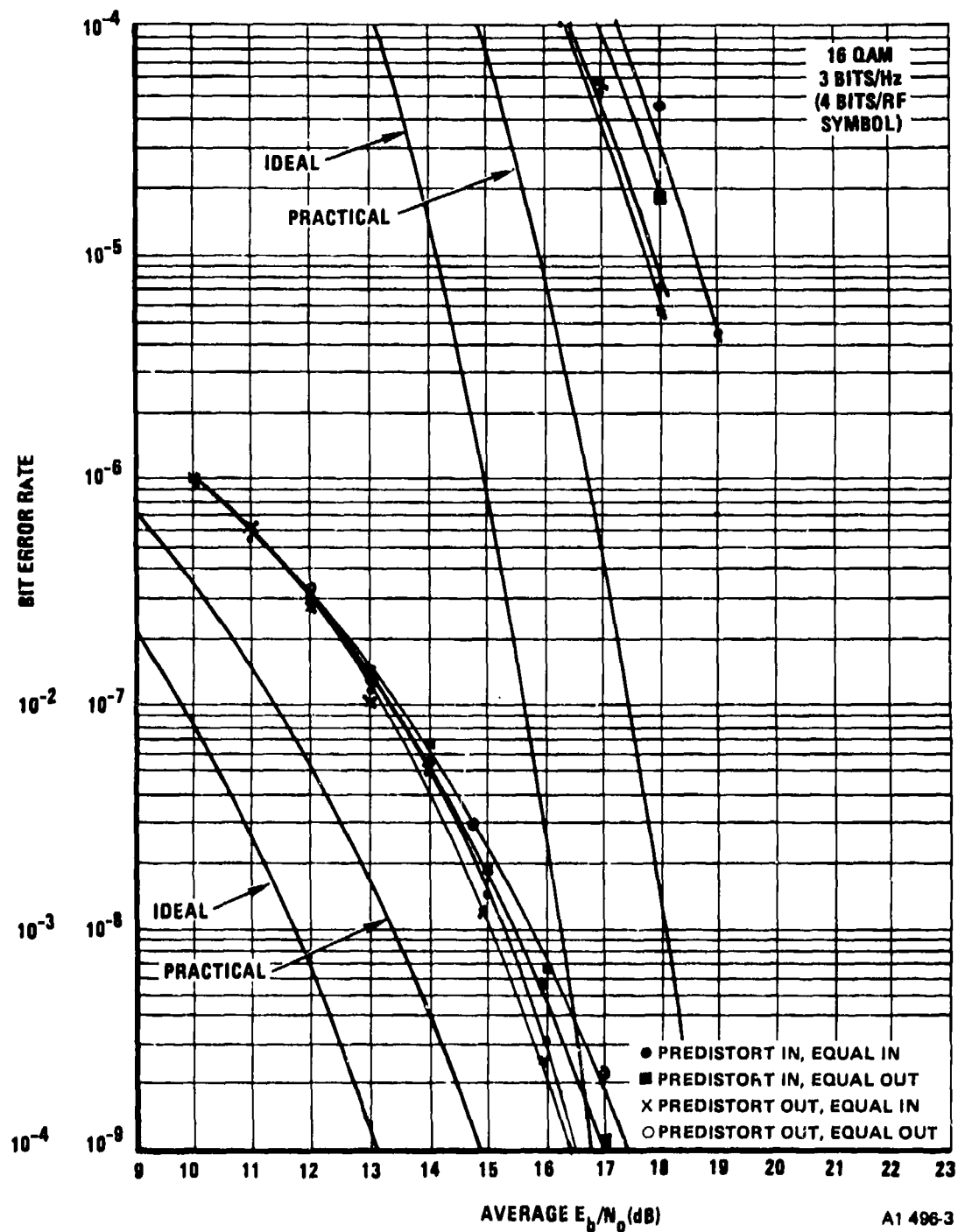


Figure 4.1.3.3-7. 16-QAM Performance With TWT 15 dB from Saturation



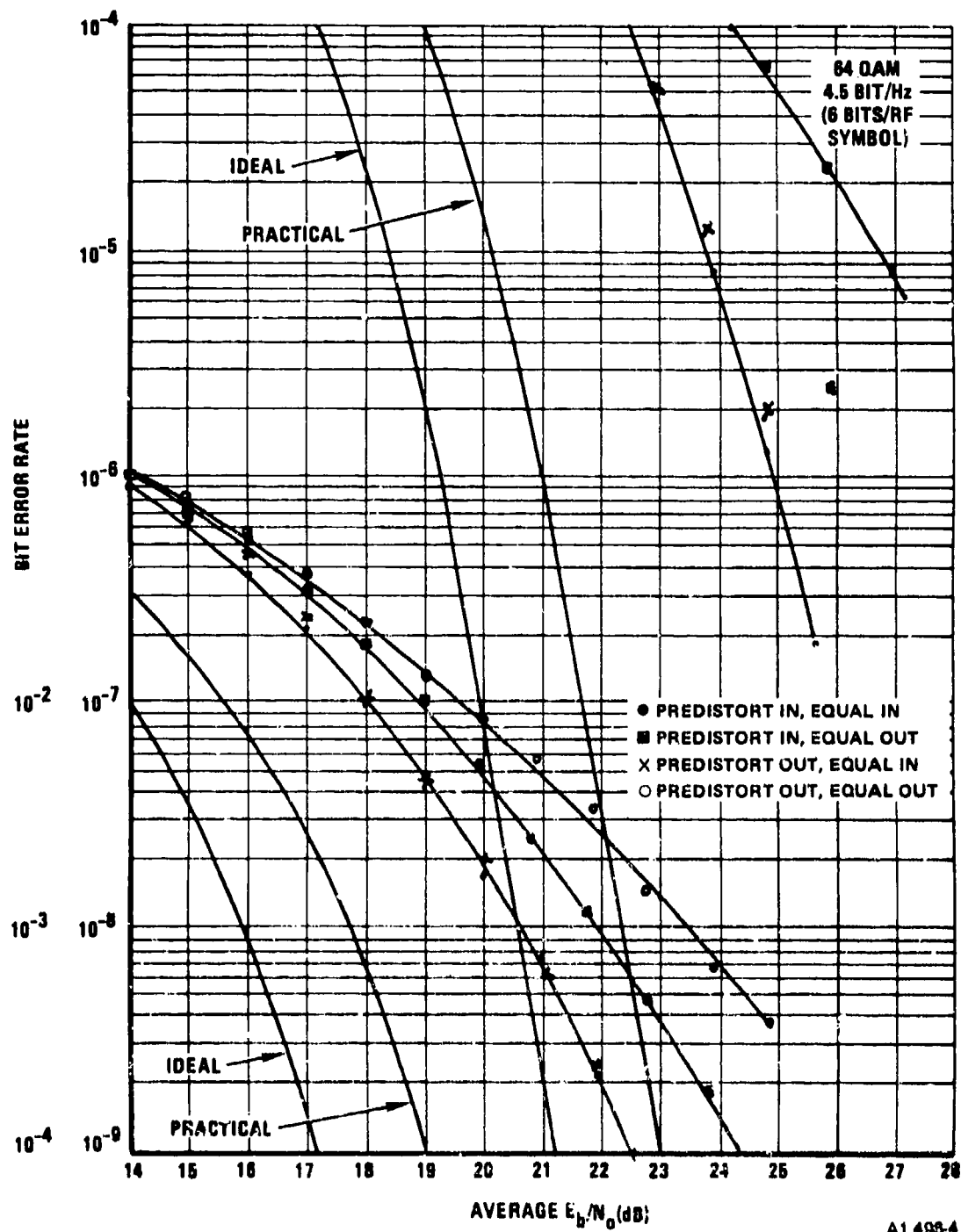


Figure 4.1.3.3-8. 64-QAM Performance With TWT 15 dB from Saturation

When the TWT was 10 dB from saturation, degradation (Figures 4.1.3.3-9 through 4.1.3.3-11) due to disabling the adaptive predistortion began to become apparent. For 4-QAM, the degradation was on the order of 0.1 dB, while the degradation for 16 and 64-QAM were 0.5 dB and 1 dB, respectively.

Operating 5 dB from saturation (Figures 4.1.3.3-12 through 4.1.3.3-14) did not cause much change in 4-QAM performance, but increased 16-QAM degradation another 0.5 dB. For 64-QAM, the degradation was significant with a flaring becoming apparent at  $2 \times 10^{-3}$  BER. The degradation was on the order of 4 dB for the disabling of predistortion.

The final set of curves (Figures 4.1.3.3-15 through 4.1.3.3-17) were taken when the TWT was 1 dB from saturation. Again, 4-QAM was only slightly affected, but 16 and 64-QAM were significantly degraded with 16-QAM suffering 4 to 5 dB degradation and 64-QAM essentially unusable with a 10 percent error rate.

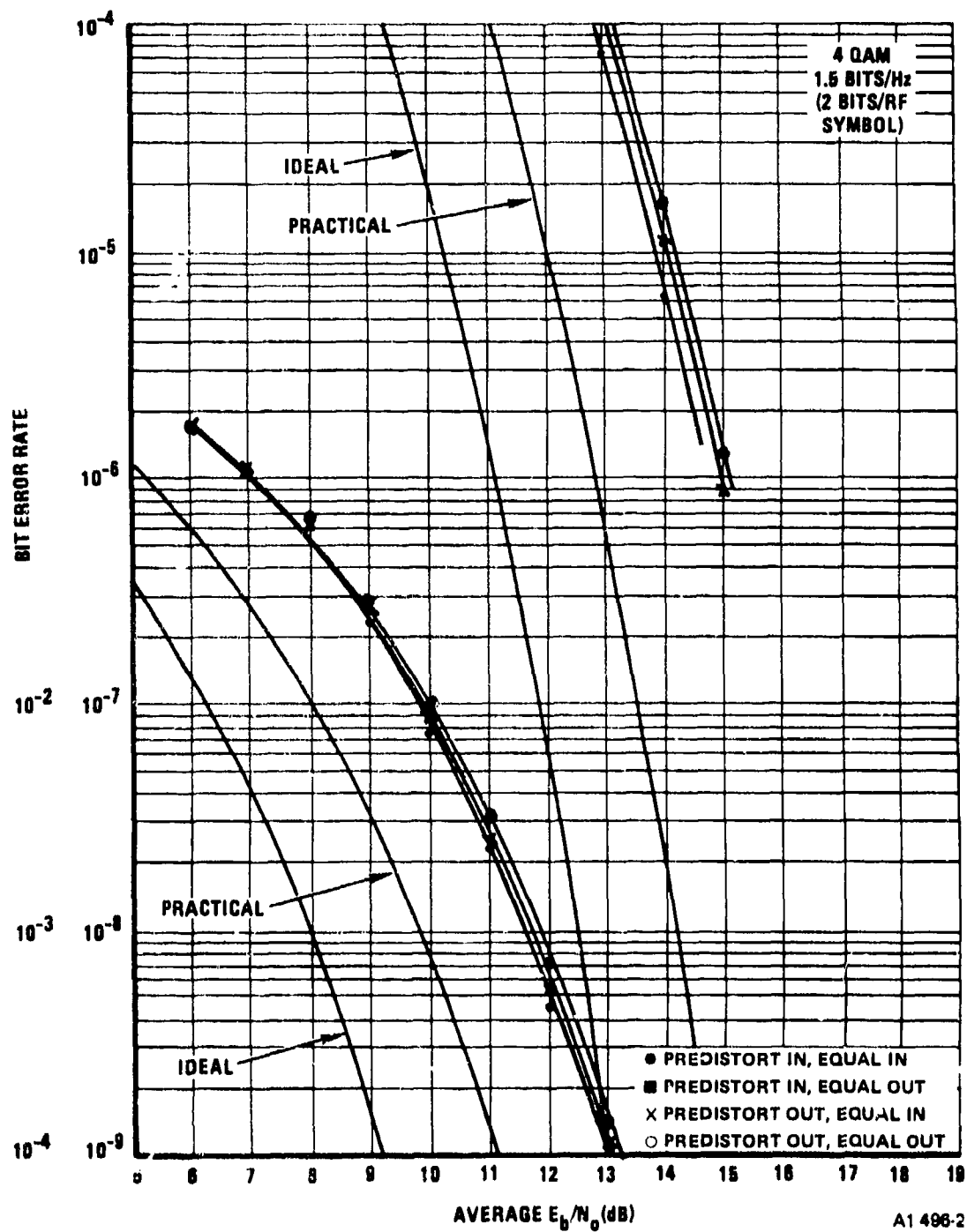


Figure 4.1.3.3-9. 4-QAM Performance With the TWT 10 dB from Saturation

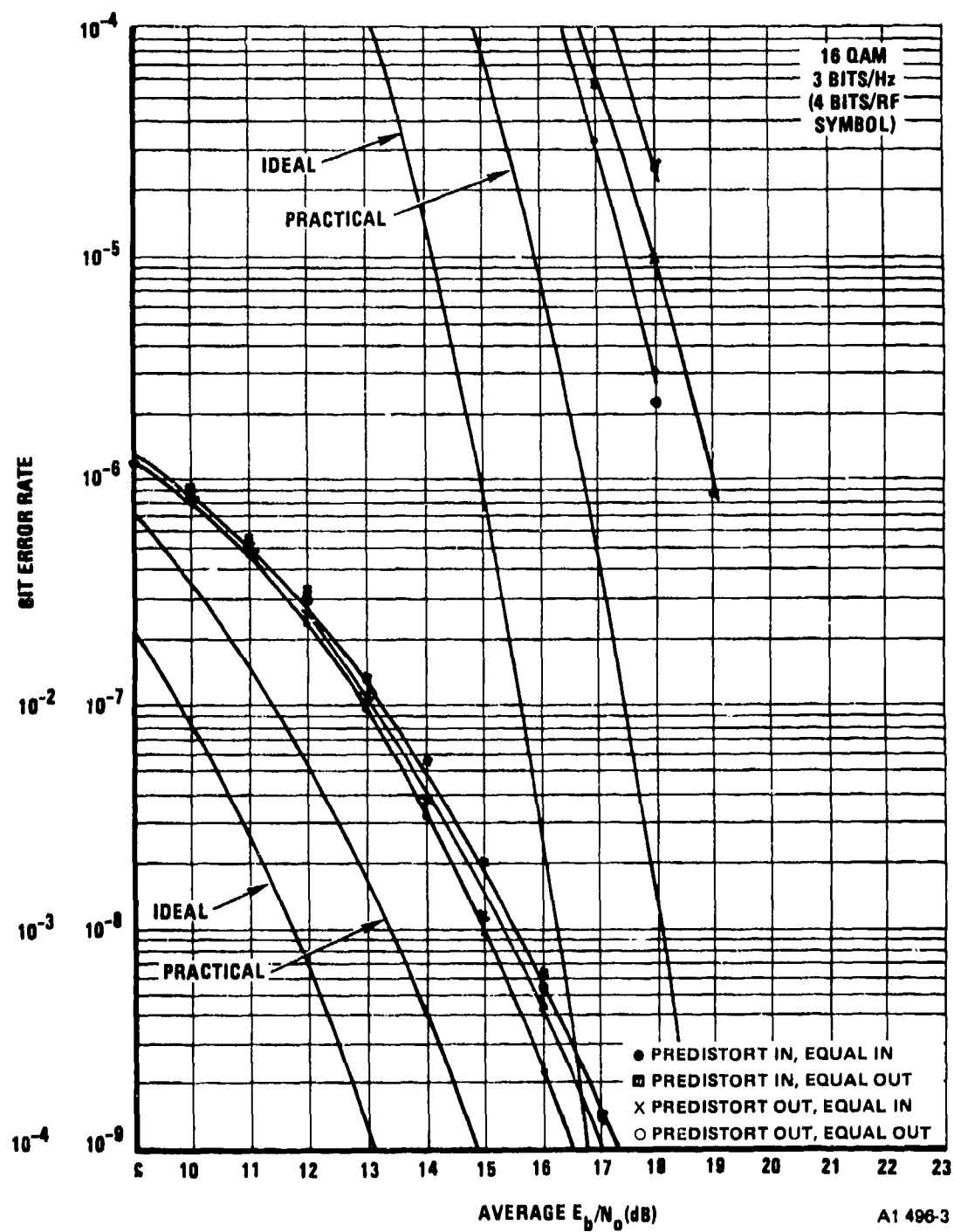


Figure 4.1.3.3-10. 16-QAM Performance With the TWT 10 dB from Saturation

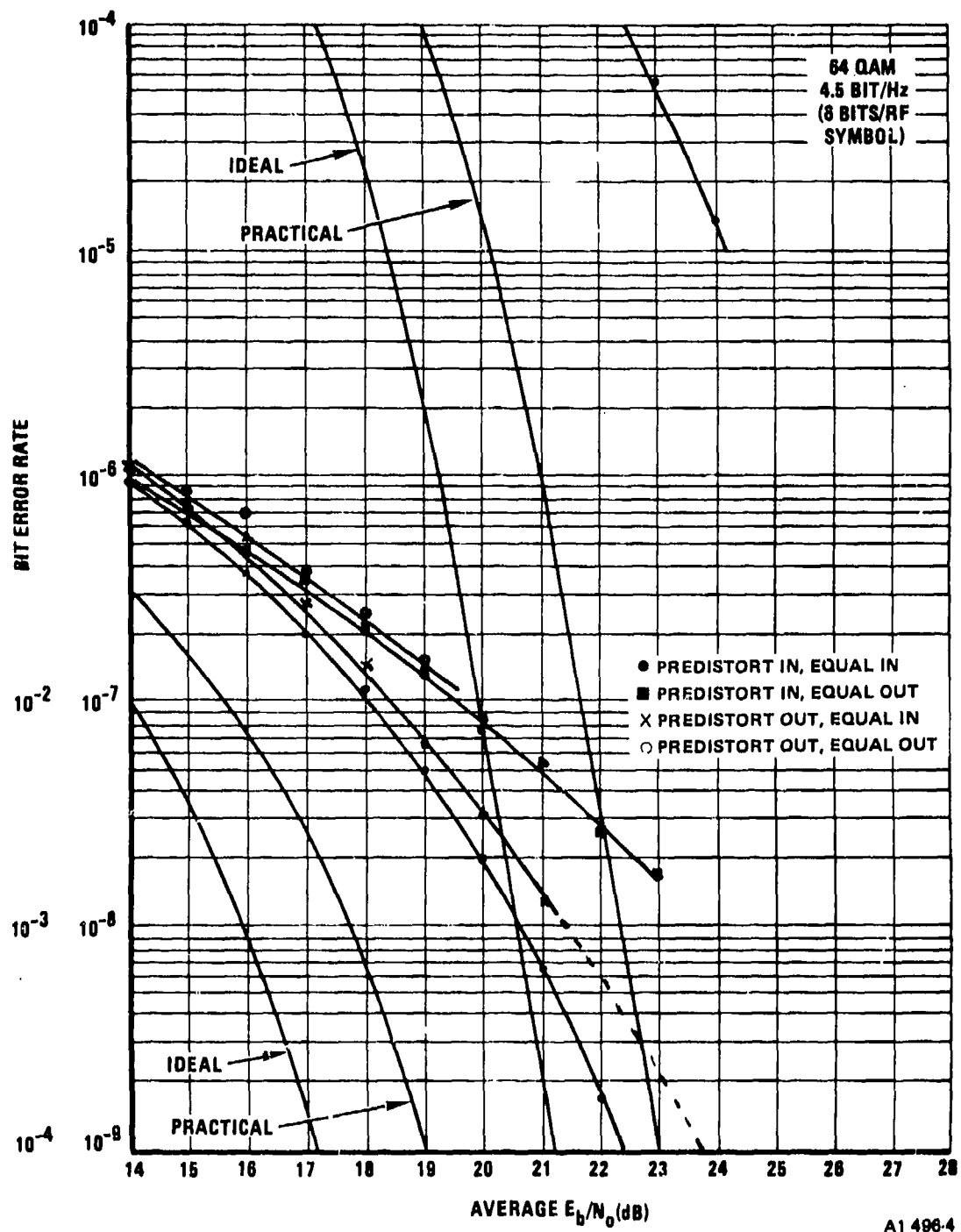


Figure 4.1.3.3-11. 64-QAM Performance With the TWT 10 dB from Saturation

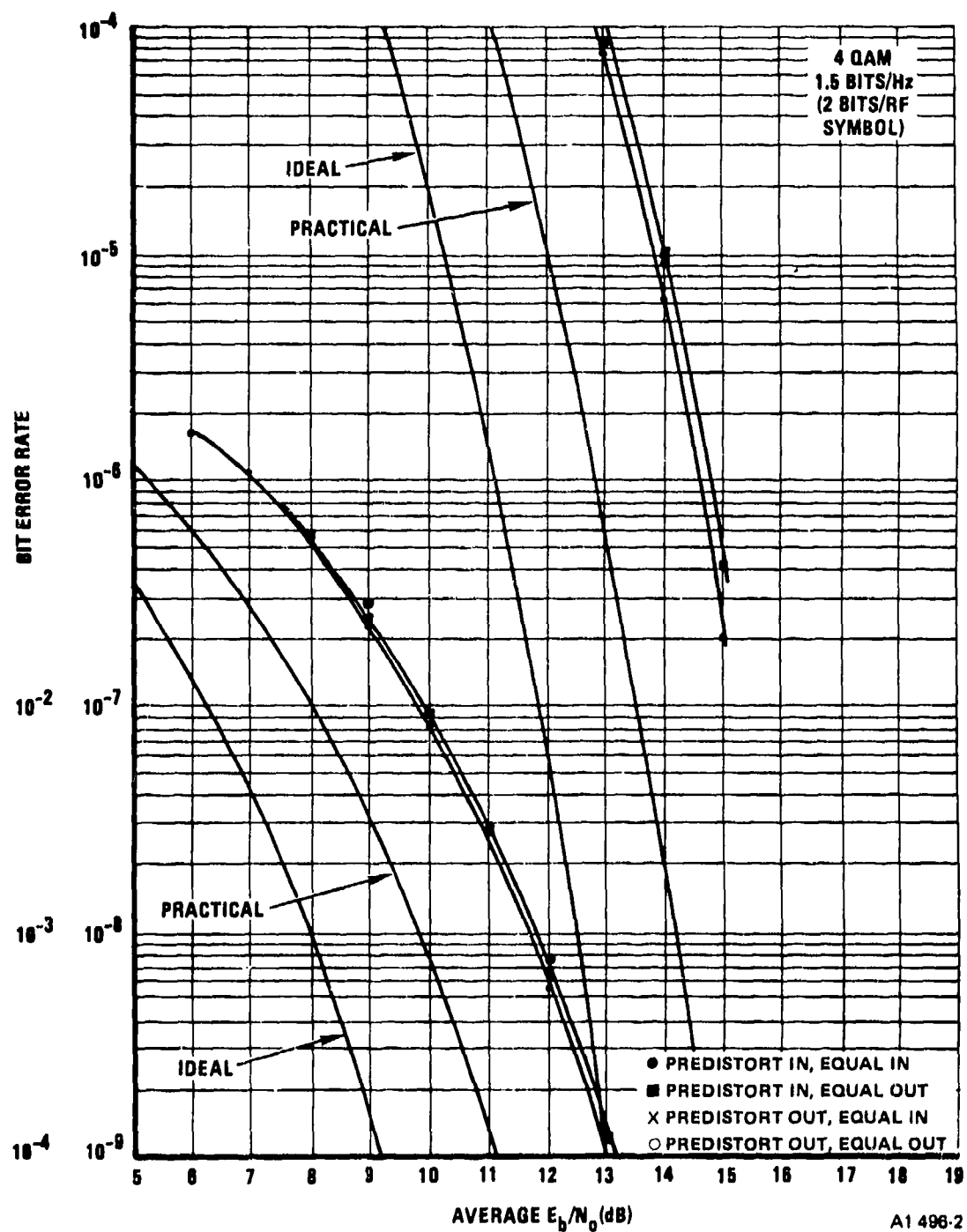


Figure 4.1.3.3-12. 4-QAM Performance With the TWT 5 dB from Saturation

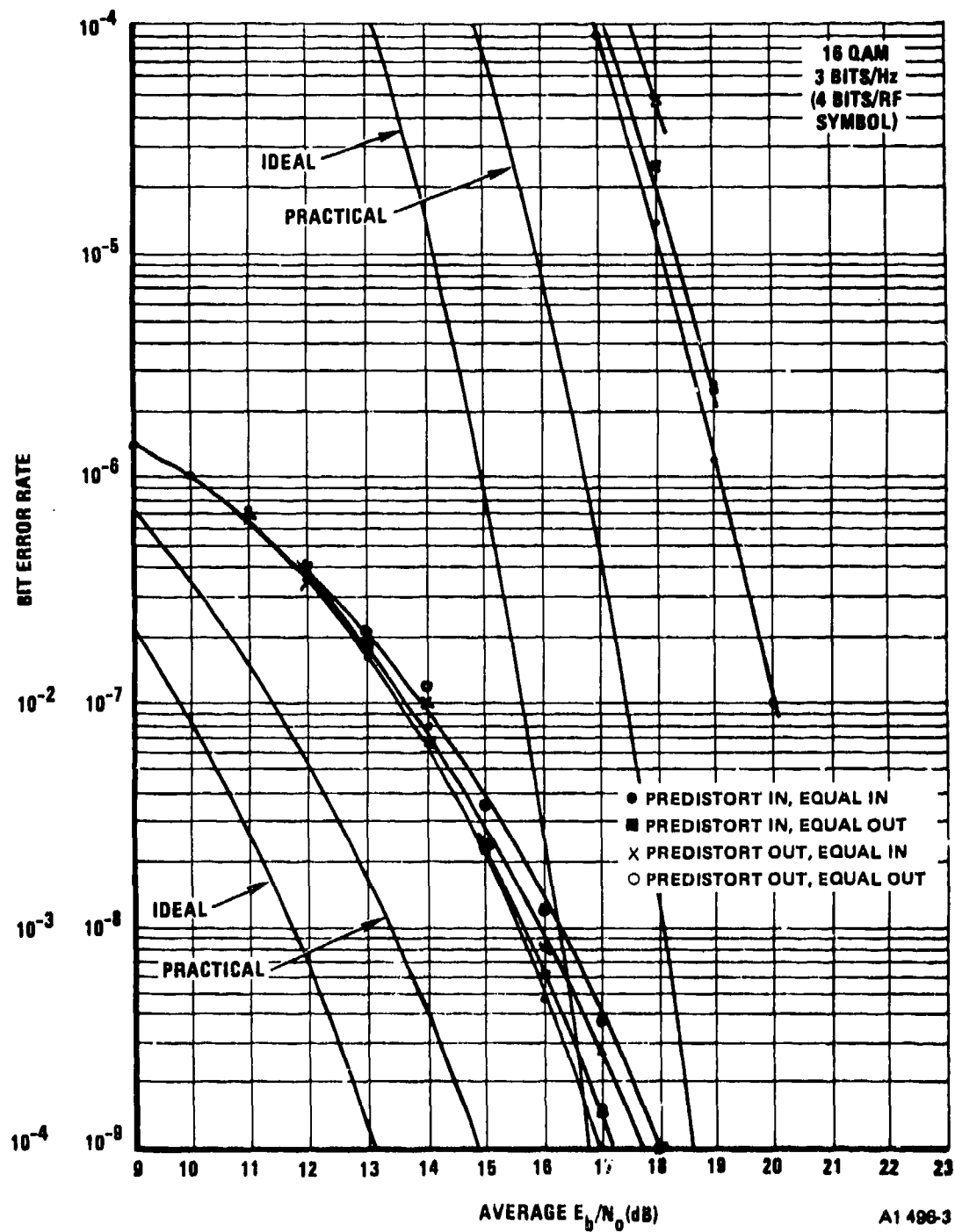


Figure 4.1.3.3-13. 16-QAM Performance With the TW 5 dB from Saturation

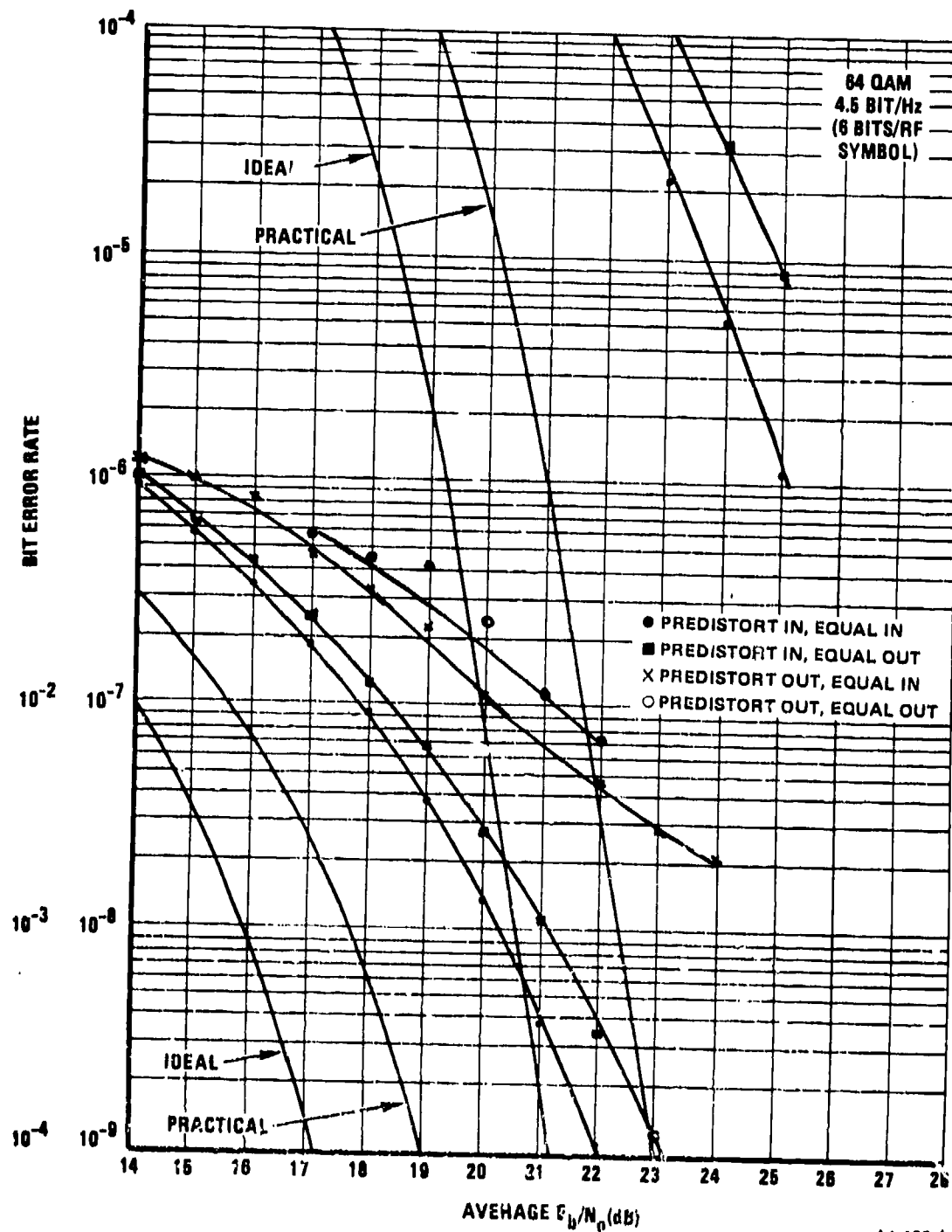


Figure 4.1.3.3-14. 64-QAM Performance With the TWT 5 dB from Saturation



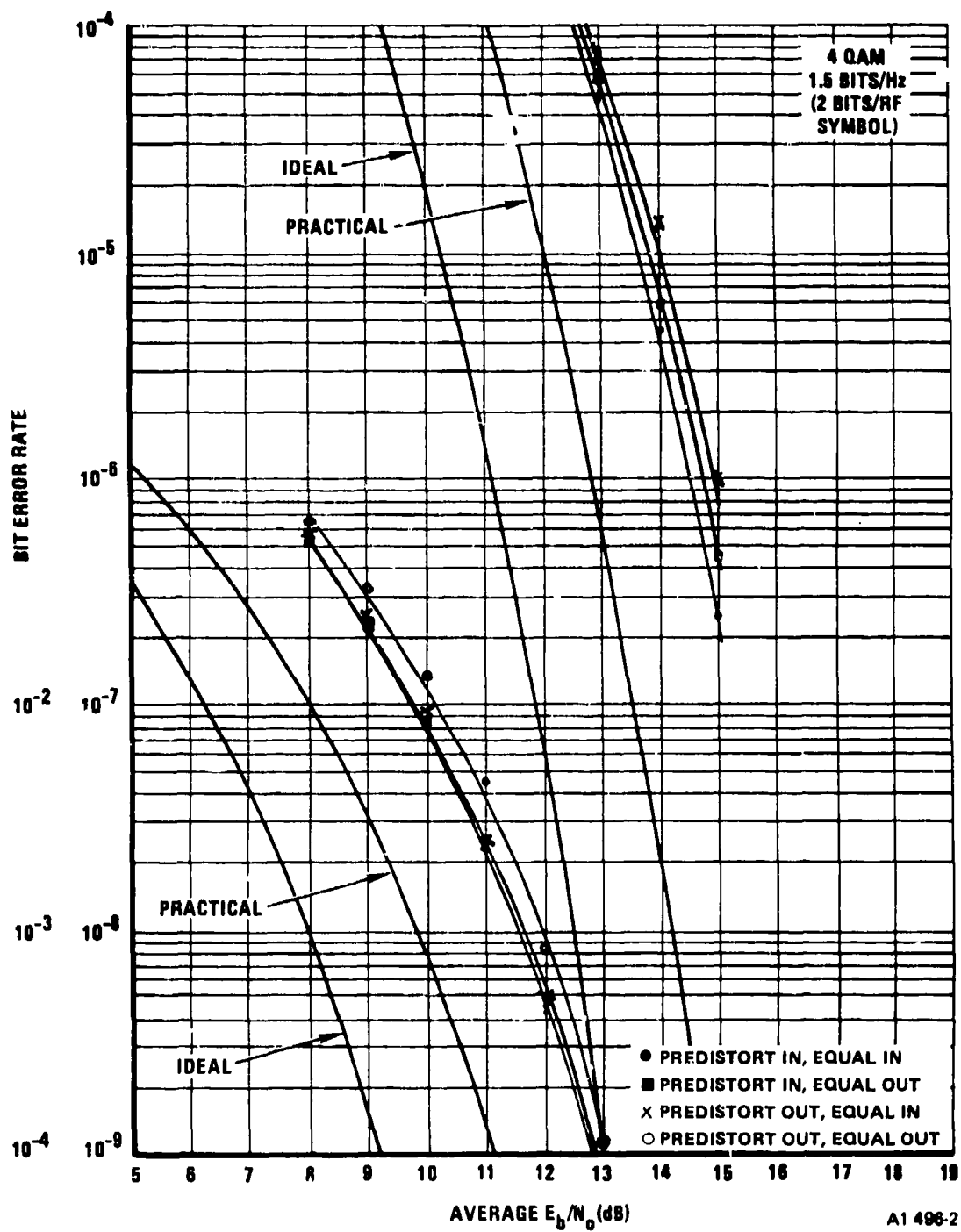


Figure 4.1.3.3-15. 4-QAM Performance With the TWT 1 dB from Saturation

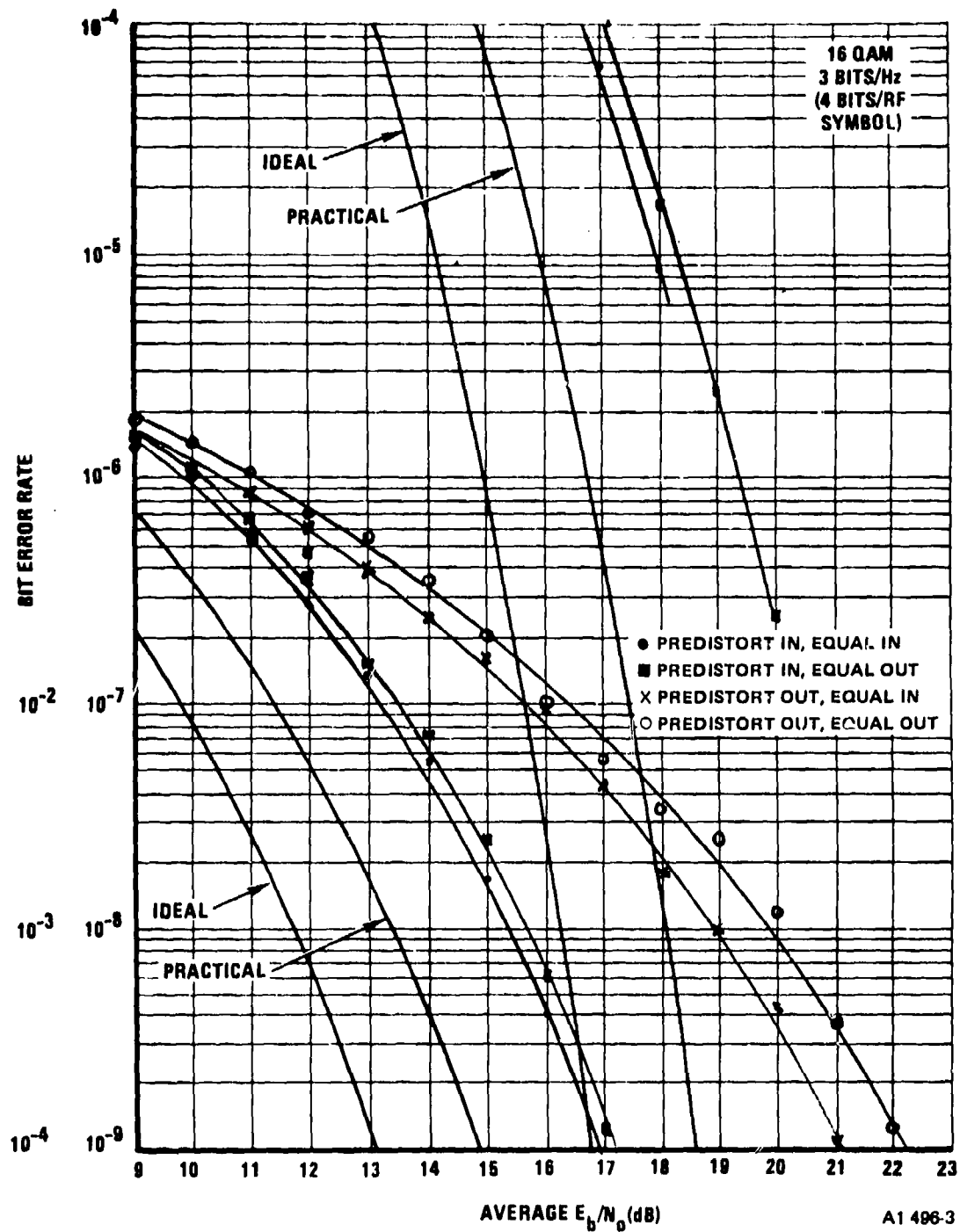
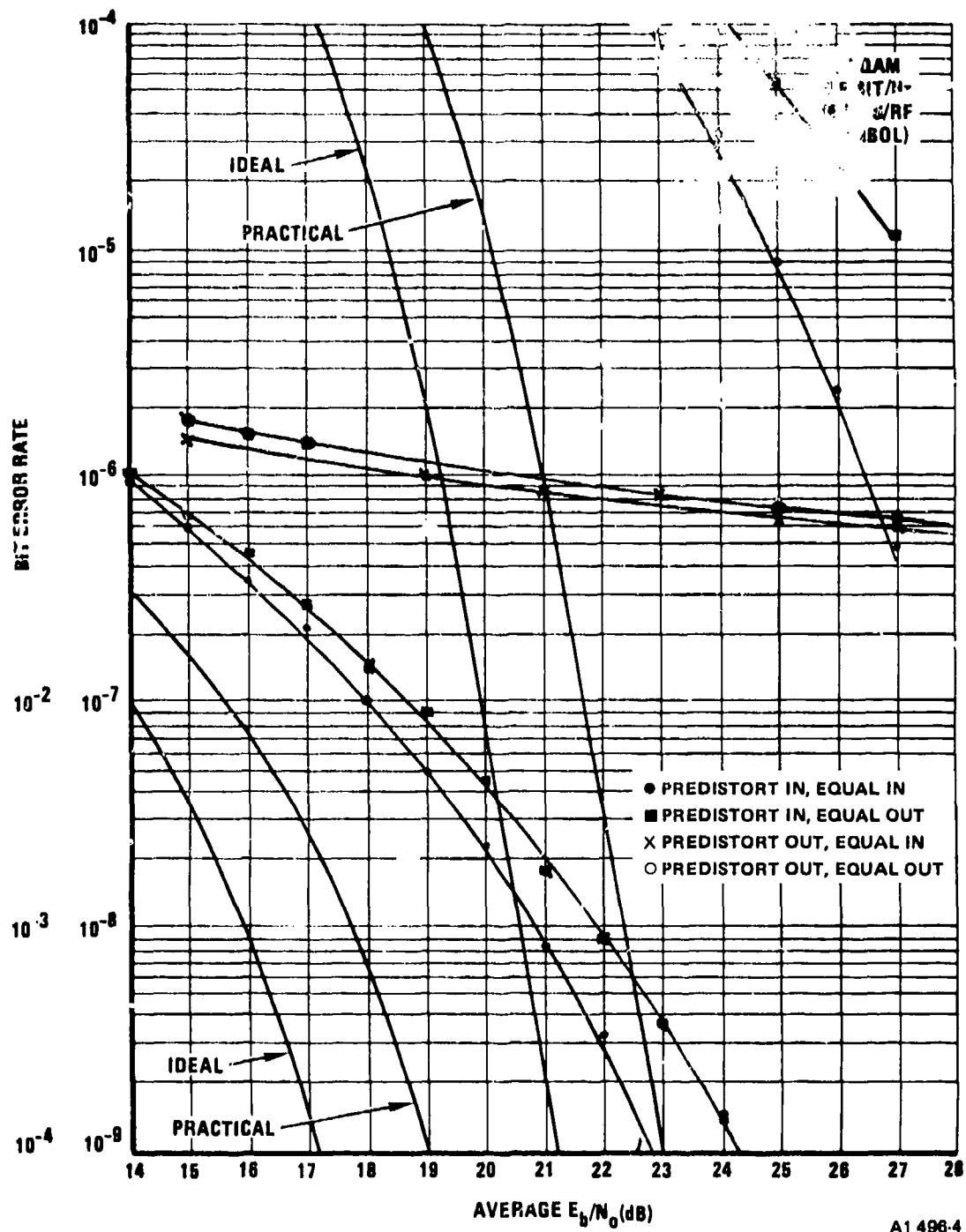


Figure 4.1.3.3-16. 16-QAM Performance With the TWT 1 dB from Saturation



## 5.0 RECOMMENDATIONS AND CONCLUSIONS

### 5.1 Conclusions

It is apparent from the data taken that 4-QAM is the most robust (as expected) of the M-QAM formats, showing little degradation with or without the adaptive predistortion or digital baseband equalizer, or for various operating points on the TWT curve. When operated 10 dB or greater from peak saturation, 16-QAM performance is acceptable without predistortion, but requires the adaptive equalizer to pick up about 0.5 dB in performance. The adaptive baseband equalizer is required at all levels of TWT loading for acceptable 64-QAM performance and adaptive predistortion is required when the TWT is operated 10 dB or less from saturation.

The concepts of adaptive predistortion and digital baseband equalization have been proven to be effective and necessary when operating at bandwidth efficiencies greater than 3 b/s/Hz within 1 dB of peak power amplifier saturation.

Although the breadboard did not meet the specifications called out in the SOW, nor did it meet the practical curves generated in Section 2.0 of this report, there is no reason to believe the performance goals could not be met with a properly designed and implemented receive filter/equalizer combination. One approach would be to use a SAW device for the receive filter, thereby easing the overall equalization requirement. One drawback to this approach would be the relatively high ( $\cong$  \$10K) tooling charges for a non-off-the-shelf unit.

### 5.2 Recommendations

The basic design concepts used in the M-QAM breadboard worked well. However, any future modem of this type should expand the digital baseband equalizer to more than 4 taps and should include the capability of adaptively compensating for I and Q channel crosstalk caused by filter amplitude tilt.

The next step in this Modem development should add the carrier and symbol timing recovery loops to the receiver in order to determine the degradation introduced by the loops. Design of these loops to meet the requirements called out in the LMT study is non-trivial.

Once receiver loops have been added, the Modem should be run over-the-air in order to determine performance in the face of rain-induced fading and multipath.

## APPENDIX A

### TEST PLAN

## A1.0 SCOPE

This plan describes a test program for the M-QAM Modem Verification Program. The tests will be conducted at Harris GCSD in Melbourne, Florida.

## A2.0 OBJECTIVE

The overall objective is to prove the predistortion and baseband equalization techniques, as well as characterize the critical performance parameters of the M-QAM Modem breadboard. Specific tests include:

- a. Verification of FCC 19311 spectral mask.
- b. Back-to-back testing at 70 MHz.
- c. Back-to-back testing through the FCC 19311 filter at 70 MHz.
- d. Simulated link tests at 5 GHz.

## A3.0 HARDWARE DESCRIPTION

The M-QAM Modem breadboard consists of a series of circuit cards and modules bolted to aluminum plates and appropriately interconnected. Power is supplied via laboratory power supplies.

The Modulator is made up of the Transmit Logic Card, Clock Generator Card, Reference Generator Card, I and Q D/A Card, Modulator Card, Downconverter Card, Error Comparator Card, and the Error Generator Card. See Figure A3.0-1 for the transmitter block diagram.

The Demodulator is made up of the Receive Logic Card, the Receive Analog Card, the A/D Converter Cards, and the test D/A Card. The test D/A Card is used for displaying signal constellations and other signals as required during test and debug. The demodulator block diagram is shown in Figure A3.0-2.

For a detailed description of the Modem hardware, refer to the "Design Plan for the M-QAM Modem Verification Program" previously submitted on this contract.

#### A4.0 TEST PROGRAM

All testing on the M-QAM Modem will be performed at the Harris GCSD facilities in Melbourne, Florida. These tests are designed to demonstrate the performance of the predistortion algorithm and baseband equalizer.

##### A4.1 FCC 19311 Spectral Mask

Spectral occupancy of the M-QAM signal will be determined by measuring the filter output with a spectrum analyzer. The power difference between the spectrum analyzer IF bandwidth and a 4 kHz bandwidth will be calculated in order to properly calibrate the display. Measure the output power with a power meter in order to calibrate the 0 dB point of the FCC mask, as shown in Figure A4.1.



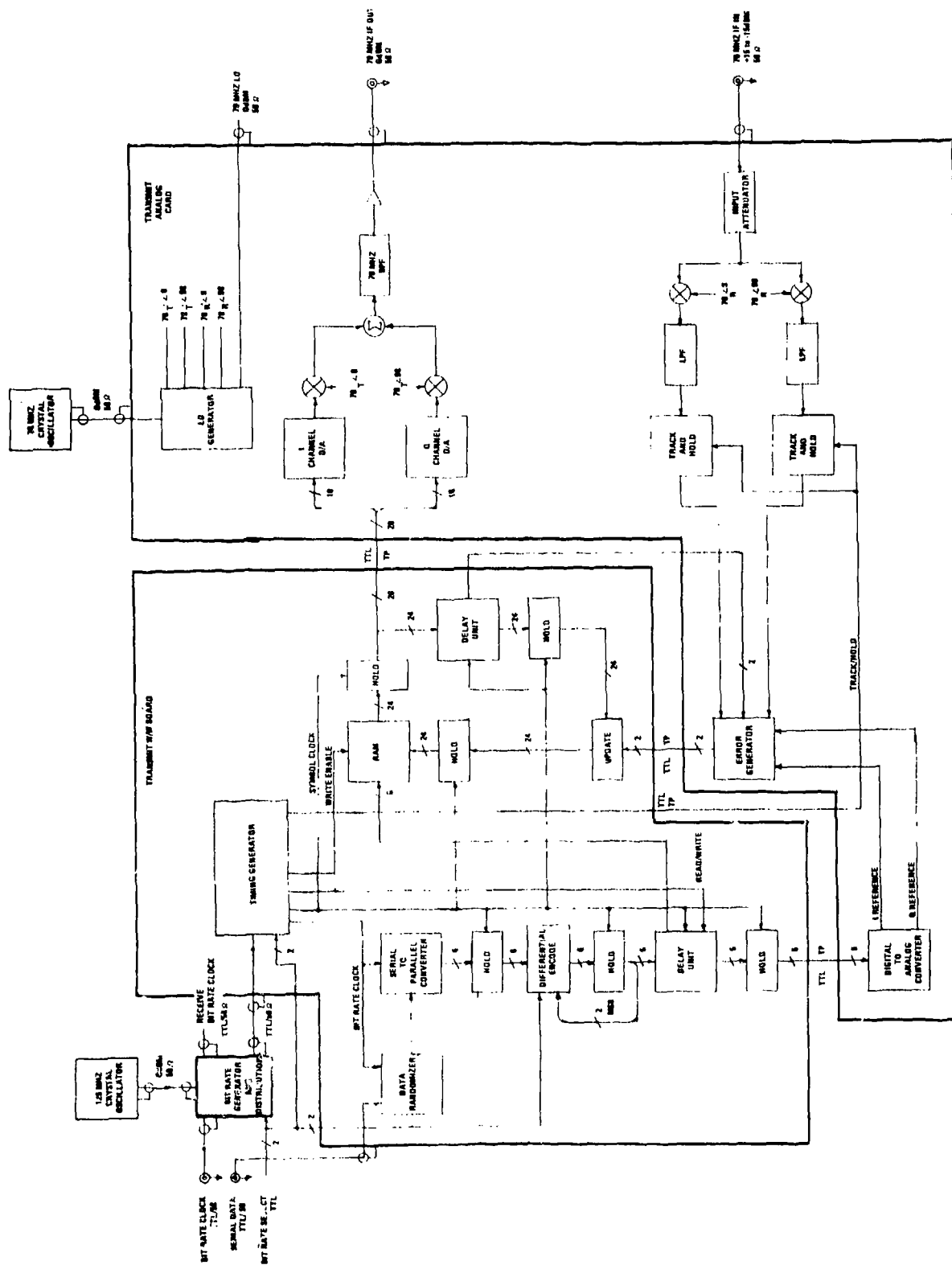


Figure A3.0-1. Transmitter Block Diagram

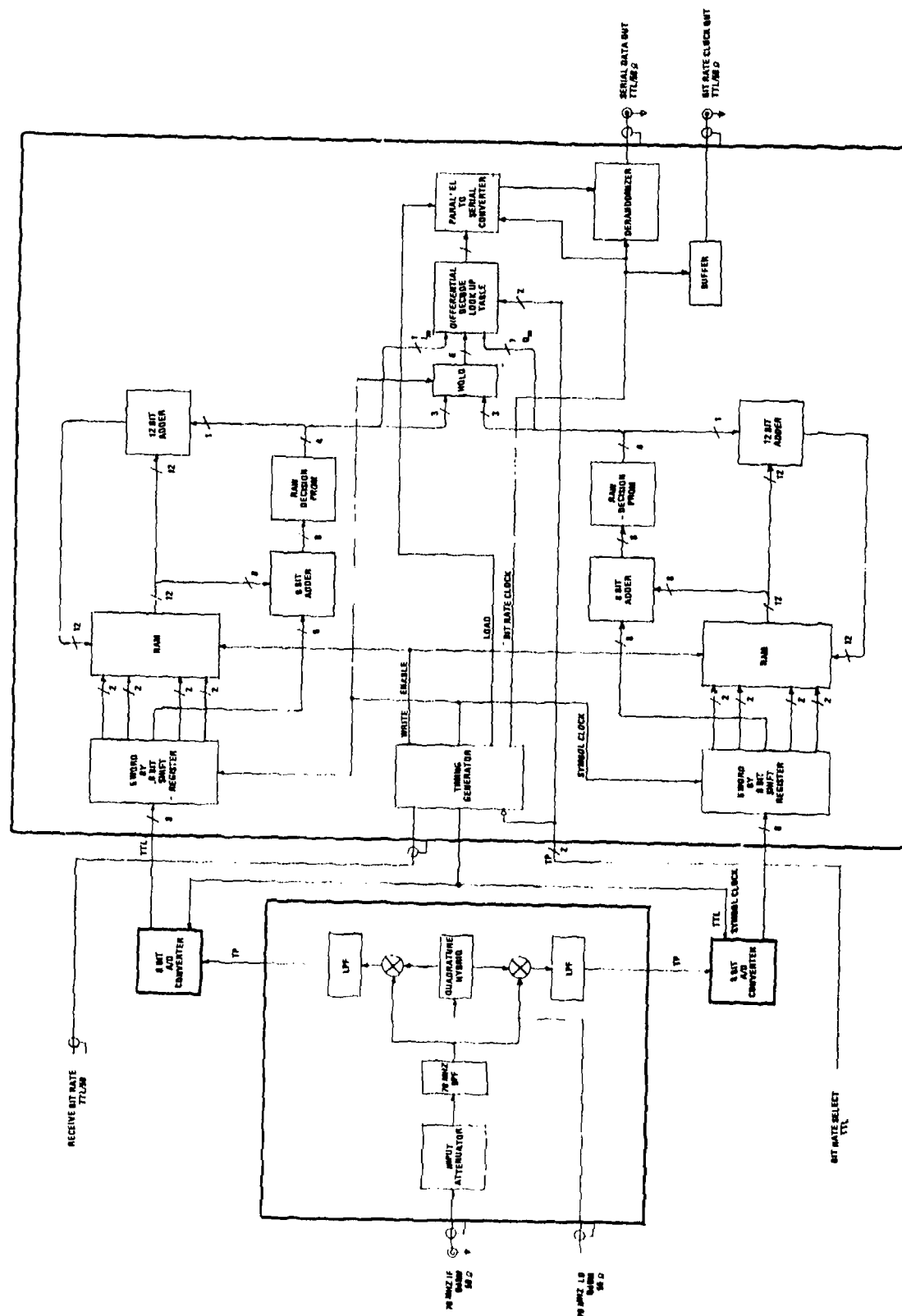
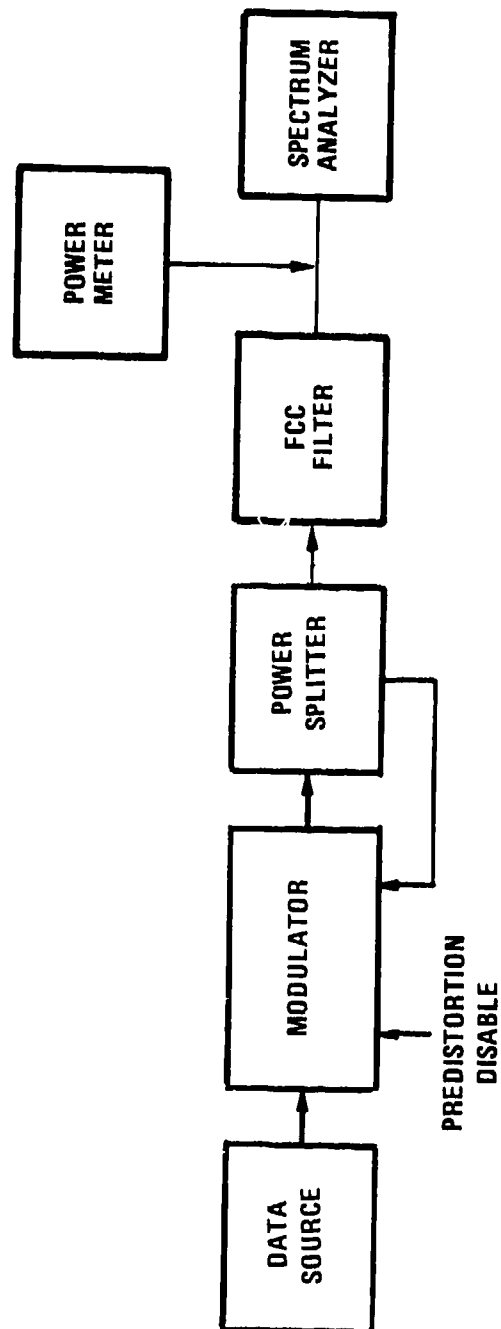


Figure A3.0-2. Demodulator  
Block Diagram



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Figure A4.1. Test Setup for FCC Mask Verification

#### A4.2 Back-to-Back (with FCC Filter)

After completion of the tests in Paragraph A4.1, the following tests will be run:

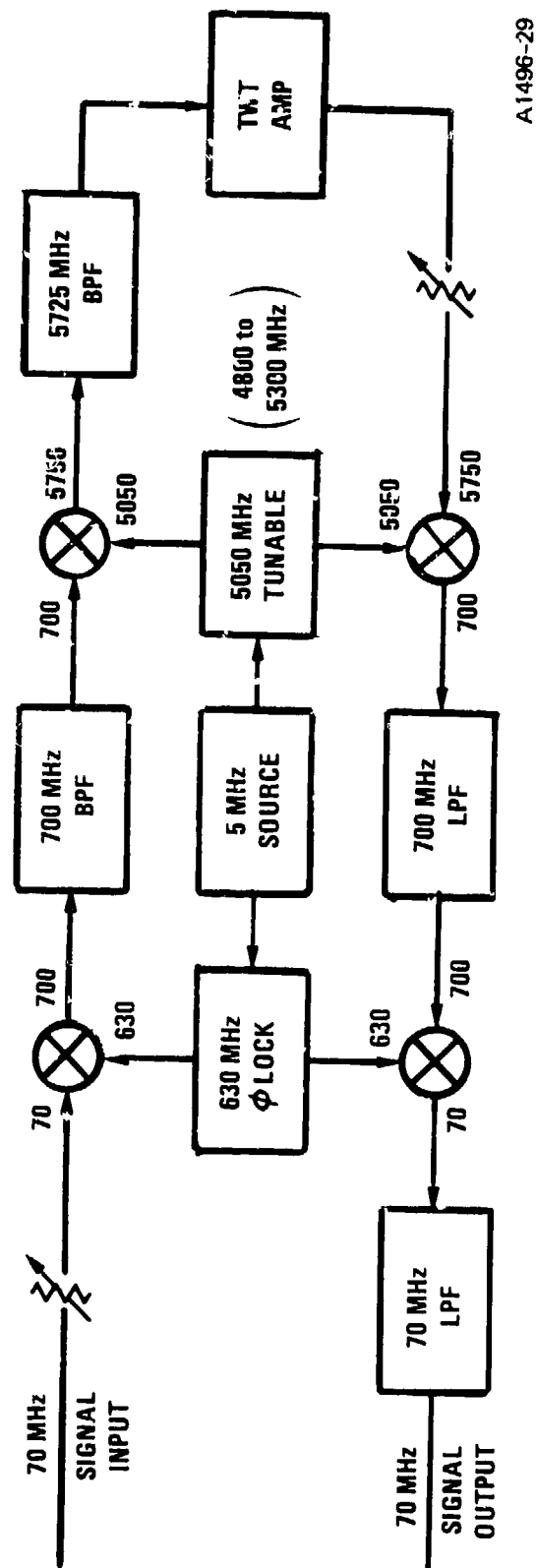
- a. Bit error rate with fixed equalizer and predistortion.
- b. Bit error rate with fixed equalizer and active predistortion.
- c. Bit error rate with active equalizer and fixed predistortion.
- d. Bit error rate with active equalizer and predistortion.

#### A4.3 Simulated Link Tests

These tests will be run using the link simulator shown in Figure A4.3-1. This simulator provides up and downconversion at 5 GHz and uses a 5 GHz TWT to produce one-watt power outputs. The TWT is capable of operating at various power levels in order to provide varying amounts of AM to PM distortion.

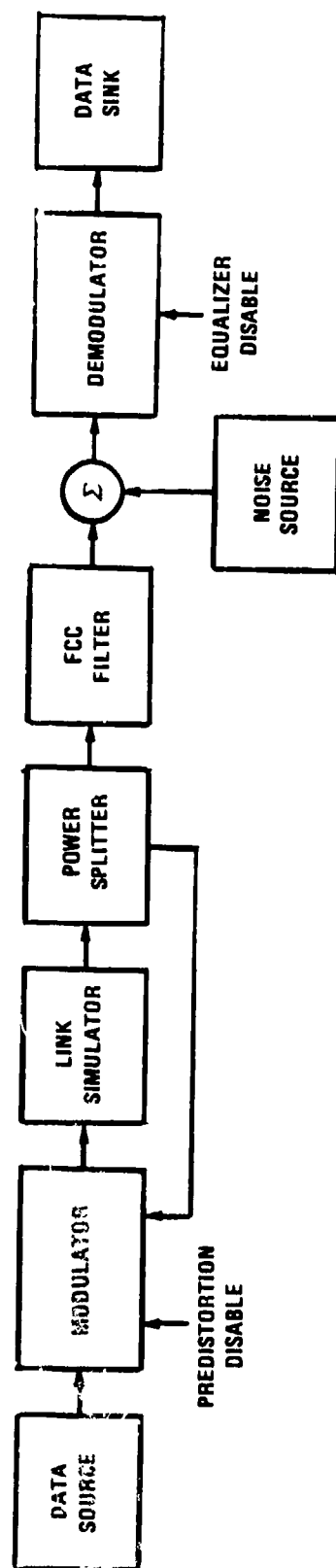
The following tests, shown in Figure A4.3-2, will be run for several values of TWT power.

- a. Bit error rate with fixed equalizer and predistortion.
- b. Bit error rate with fixed equalizer and active predistortion.
- c. Bit error rate with active equalizer and fixed predistortion.
- d. Bit error rate with active equalizer and predistortion.



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Figure A4.3-1. Link Simulator

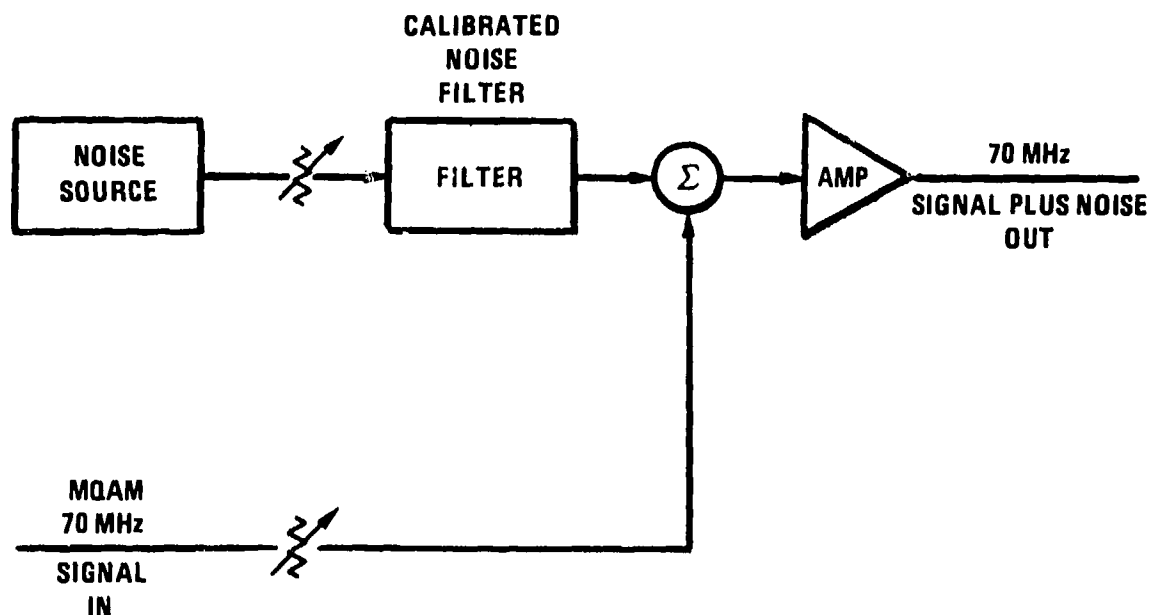


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Figure A4.3-2. Simulated Link Test

#### A4.4 $E_b/N_0$ Calibration

The test setup for Figure A4.4 is used to provide a reference error rate for the Broadband Modem. Thermal noise power at the output of the test setup is measured with the signal attenuator set to maximum attenuation. This measurement is recorded. The noise attenuator is then set to maximum attenuation and the signal attenuator is adjusted to give the same meter reading as the noise power did previously. The noise attenuator is then restored to its original position, establishing a 0 dB SNR in the filter bandwidth.  $E_b/N_0$  is obtained by adjusting the attenuator output.



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Figure A4.4.  $E_b/N_0$  Calibration

#### A5.0 TEST PROCEDURES

The following paragraphs present the detailed test procedures required to perform the tests described in Section 4.0 of this document.

#### A5.1 FCC 19311 Spectral Mask

1. Connect the M-QAM breadboard, as shown in Figure A4.1, with the HP3760A Data Generator as the data source and the HP3761A Error Analyzer as the data sink.
2. Set the M-QAM MODE switch to 4-QAM.
3. Measure and record the power out of the mask filter.
4. Use a frequency synthesizer and calibrate the spectrum analyzer.
5. Set the spectrum analyzer to 0.5 MHz/div and 30 kHz IF bandwidth.
6. Record the spectrum trace.
7. Set the spectrum analyzer for 1 MHz/div.
8. Record the spectrum trace.

The FCC mask 0 dB point is equal to the power meter reading,  $P_m$ . The FCC mask 50 dB point is located at  $70 \pm 1.75$  MHz at a level equal to  $P_m - 50 + 10 \log \left( \frac{30 \text{ kHz}}{4 \text{ kHz}} \right)$ . The FCC mask 80 dB point is located at  $70 \pm 3.5$  MHz at a level equal to  $P_m - 80 + 10 \log \left( \frac{30 \text{ kHz}}{4 \text{ kHz}} \right)$ .

#### A5.2 Back-to-Back (With FCC Filter)

1. Connect the M-QAM breadboard, as shown in Figure A4.1, with the HP3760A as the data source and the HP3761A as the data sink. Adjust the receive level to bring it back to the value it had in A5.1(1.).



2. Set the M-QAM MODE switch to 4-QAM and disable the predistortion and equalizer circuits.
3. Refer to Paragraph A4.2 and set the  $E_b/N_0$  to 9 dB.
4. Record the error rate on the appropriate data sheet.
5. Repeat Steps A5.2(3.) and A5.2(4.), increasing the  $E_b/N_0$  by 0.5 dB each time until the error rate is better than  $10^{-9}$ .
6. Repeat Steps A5.2(2.) through A5.2(5.), except set the MODE to 16-QAM and start with  $E_b/N_0$  at 14 dB.
7. Repeat Steps A5.2(2.) through A5.2(6.) for 64-QAM and with  $E_b/N_0$  starting at 18 dB.
8. Repeat Steps A5.2(2.) through A5.2(7.), except enable the predistortion circuitry.
9. Repeat Step A5.2(8.) with the equalizer enabled and predistortion enabled.
10. Repeat Step A5.2(8.) with the equalizer and predistortion enabled.

### A5.3

#### Simulated Link Test

1. Connect the M-QAM breadboard, as shown in Figure A4.3-2, with the HP3760A as a data source and the HP3761A as a data sink. Adjust the TWT to be 15 dB below saturation and adjust the M-QAM receive level for proper operation.
2. Set the M-QAM MODE switch to 4-QAM and disable the predistortion and equalizer circuits.

3. Refer to Paragraph A4.2 and set  $E_b/N_0$  to 9 dB.
4. Record the error rate on the appropriate data sheet.
5. Repeat Steps A5.3(3.) and A5.3(4.), increasing  $E_b/N_0$  by 0.5 dB each time until the error rate is better than  $10^{-9}$ .
6. Repeat Steps A5.3(2.) through A5.3(5.) with the MODE switch set to 16-QAM and with  $E_b/N_0$  starting at 14 dB.
7. Repeat Step A5.3(6.) for 64-QAM and  $E_b/N_0$  starting at 18 dB.
8. Repeat Steps A5.3(2.) through A5.3(7.) with predistortion enabled.
9. Repeat Step A5.3(8.) with the equalizer enabled and predistortion disabled.
10. Repeat Step A5.2(8.) with the equalizer and predistortion enabled.
11. Repeat Steps A5.3(2.) through A5.3(10.) with the TWT 10 dB from saturation.
12. Repeat Step A5.3(11.) with the TWT 5 dB from saturation.
13. Repeat Step A5.3(12.) with the TWT 1 dB from saturation.

## DATA SHEETS

The following figures show the format in which data will be recorded. Each M-QAM mode (4, 16, and 64) is represented on a different sheet and each sheet contains the predicted performance curve as a reference. Bit error rate versus  $E_b/N_0$  will be plotted directly on these sheets so that actual versus predicted error rate curves can be easily compared. Information as to the test conditions will be typed directly on the data sheet.

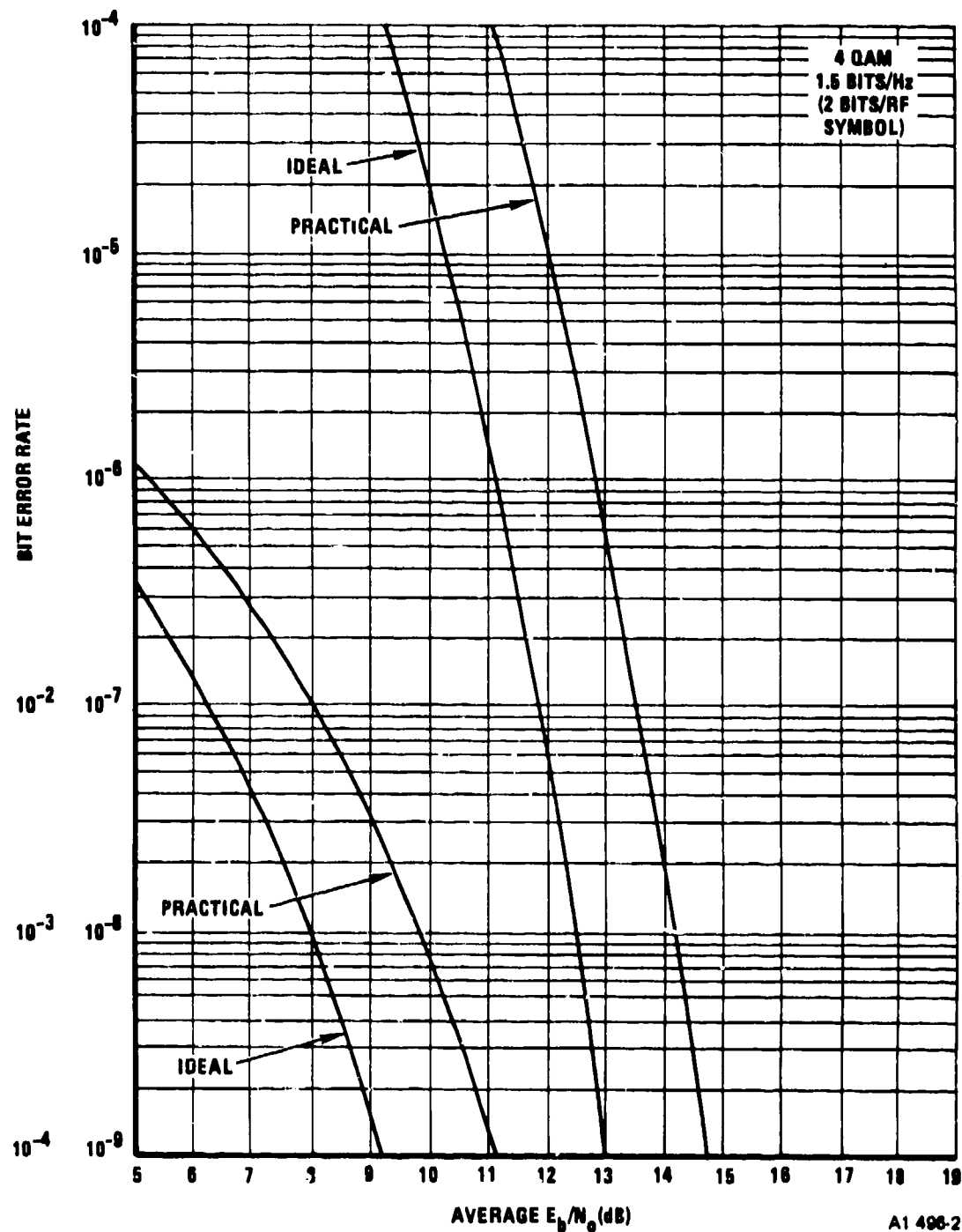


Figure A1. 4-QAM

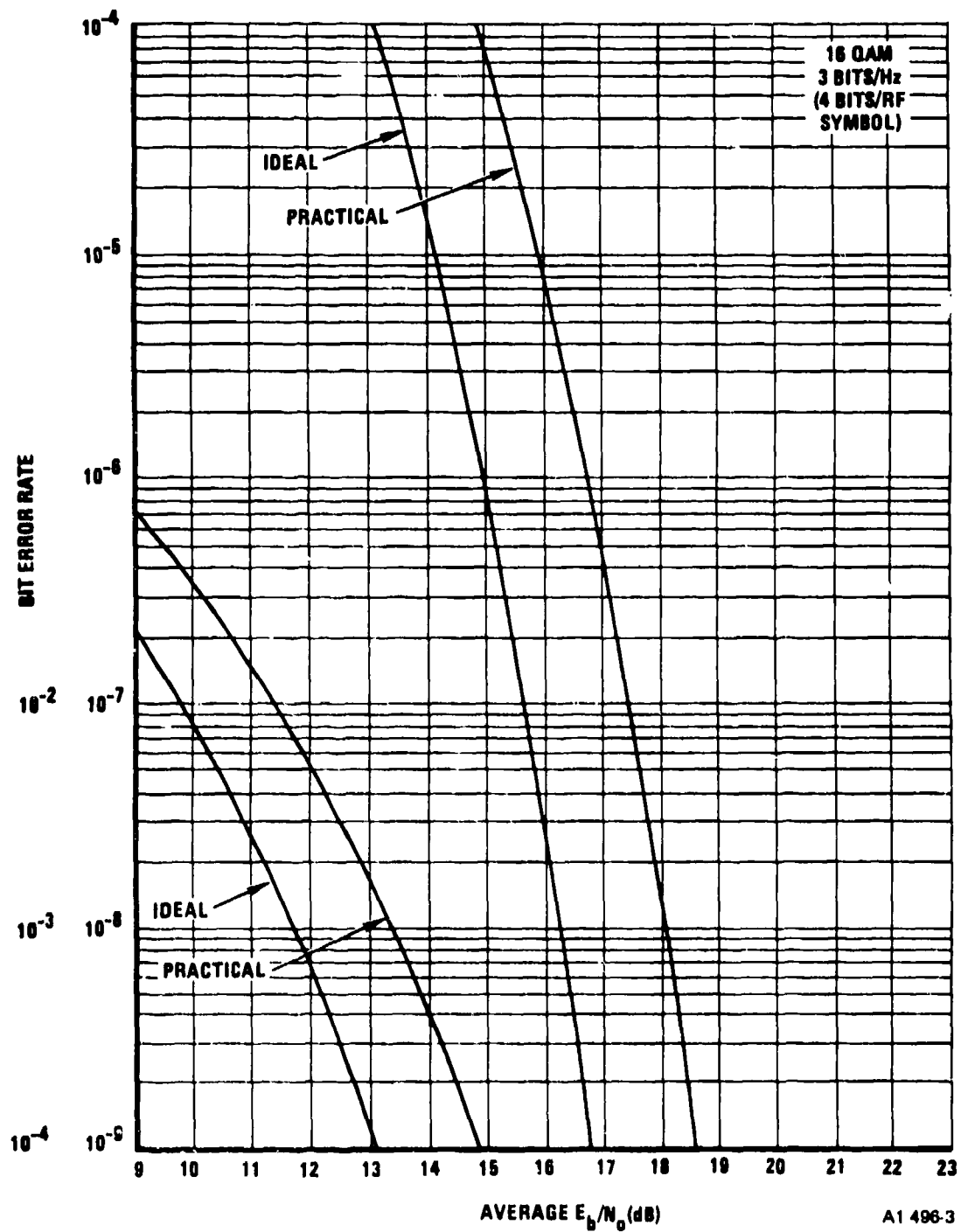


Figure A2. 16-QAM

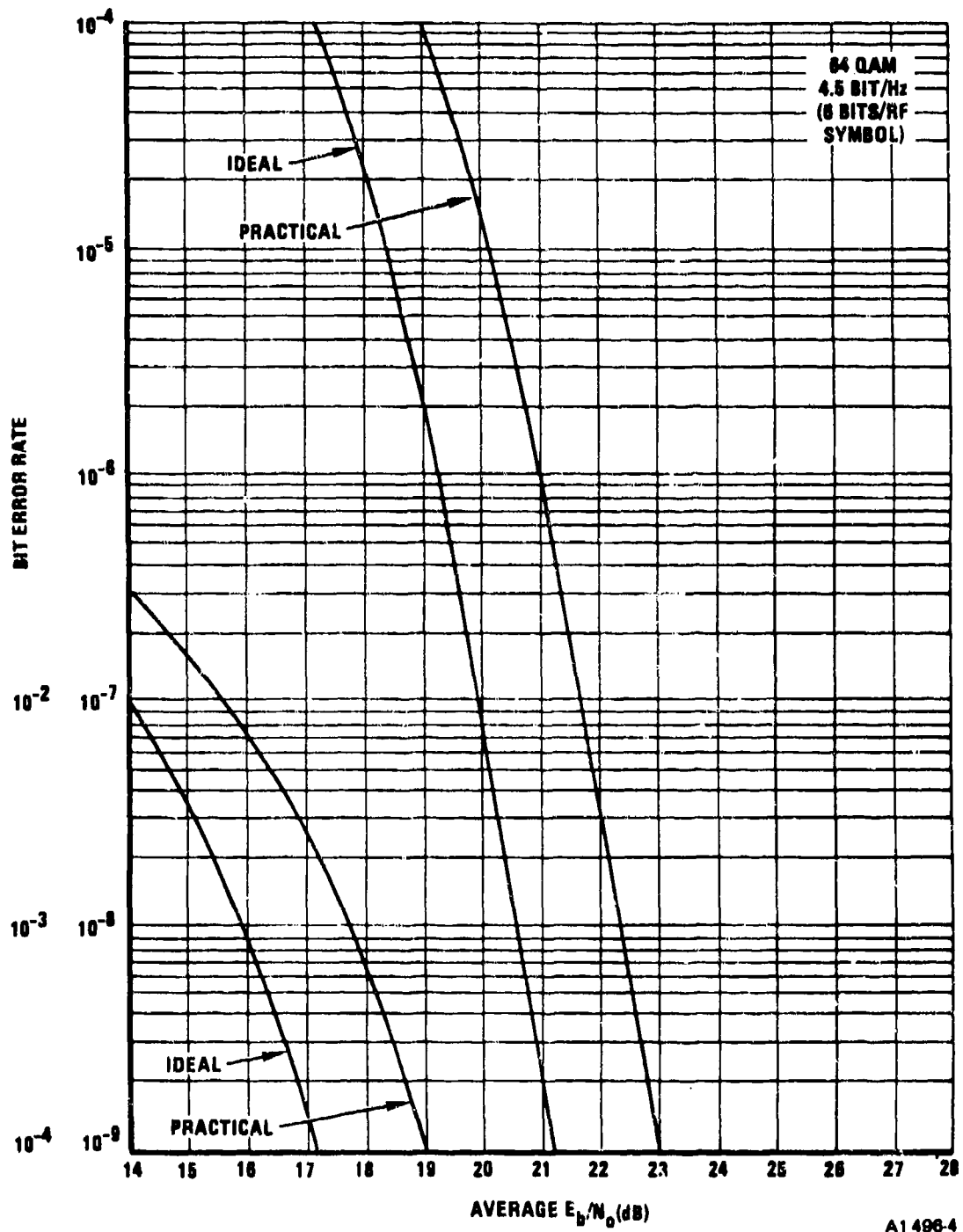


Figure A3. 64-QAM

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- 1) "Linear Modulation Techniques for Digital Microwave," RADC-TR-79-56, Final Technical Report, August 1979.
- 2) "ECCM for DCS III," Final Technical Report, May 1980, Contract F30602-79-C-0072.
- 3) Blinchikoll, H.J. and Zverev, A.I., "Filtering in the Time and Frequency Domains", John Wiley and Sons, 1976.
- 4) "Design Plan for a Linear Modulation Techniques Modem," Contract F30602-77-C-0039, November 1978.
- 5) "Design Plan for the M-QAM Modem Verification Program," Contract F30602-80-C-0278, December 1980.
- 6) Wozencraft and Jacobs, "Principles of Communications Engineering," John Wiley and Sons, 1967.



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